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The Environmental Effects of Coal Fires

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TITLE PAGE

THE ENVIRONMENTAL EFFECTS OF COAL FIRES

DISSERTATION

By

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ABSTRACT OF DISSERTATION
THE ENVIRONMENTAL EFFECTS OF COAL MINE FIRES

There are thousands of subterranean coal fires in the world that, because of incomplete combustion, emit a wide variety of volatile and semivolatile organic compounds to the atmosphere, water, and soil at concentrations that could pose health risks to humans and wildlife. The main goals of this study were to (1) review methods that are used to characterize physical and chemical characteristics of coal-fire sites, (2) determine relationships between gas emissions and physical and chemical characteristics of coal-fire sites, using a combination of regression and multivariate statistical methods, and (3) determine the concentrations of volatile and semivolatile organic compounds in water and soil at two coal-fire sites in eastern Kentucky. More specifically:

The objective of Chapter 1 was to review past works and list technologies used over time. Eight years of coal-fire collection technologies were reviewed. A variety of methods and technologies were identified. Qualitative and quantitative preferences were noted.

The objective of Chapter 2 was to identify and list uncontrolled coal-fire variables. These variables include complete/incomplete combustion; fire temperature and size; distance to fire; relative humidity and moisture in the system; geology, geochemistry, and age of coal; condition of the mine, sampling time of day; sampling equipment differences; and human error. A secondary objective of this chapter was to determine which coal-fire gases have strong relationships by using the principal component analysis (PCA) software JMP. The strongest relationship was between CO and H_2S. Temperature and CH_4 were also important. This indicates that incomplete combustion and polynuclear aromatic hydrocarbon (PAH) formation are likely occurring, setting the stage for Chapter 3.

The objective of Chapter 3 was to identify and define the extent of soil and water hydrocarbon contamination at the Truman Shepherd and Lotts Creek coal fires in eastern Kentucky. No groundwater contamination was detected at either location. Soil contamination was found at both, but was much higher at Lotts Creek, potentially because of sorption onto soil organic matter (which is reduced at Truman Shepherd by an excavation attempt) and other physicochemical mechanisms. Soil contamination was localized to relatively small areas around coal-fire vents.

Based on the results, future studies should consider:

- Attempting to duplicate these results in other geologic regions
- Quantifying greenhouse gas emissions from coal fires to consider their contribution to climate change. Coal-fired power plants are regulated, but coal fires, which produce many more harmful gases, are not
- Determining the feasibility of an oxygen-injection system to engender more complete combustion, therefore possibly reducing harmful gases
- Determining the feasibility of electricity production from coal fires
- Adopting a consistent federal coal-fire policy

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INTRODUCTION

Coal fires emit dangerous gases and contribute to water pollution, land subsidence, and resource loss. These fires may be ignited by lightning strikes, forest fires, or by human activity, such as trash burning or mine fires. Spontaneous combustion from exothermic reactions of coal exposed during mining is also a concern (Stracher et al., 2004). Coal fires have likely been burning intermittently since the Carboniferous; zircon evidence dates to the Pliocene in the Powder River Basin of the United States (Heffern and Coates, 2004) and the Pleistocene in northwestern China (Kroonenberg and Zhang, 1997). Written accounts of coal fires date to Alexander the Great (Stracher et al., 2005).

With more emphasis on coal since the Industrial Revolution, coal fires have increased substantially, especially in coal-producing countries such as China, India, the United States, South Africa, Russia, and Indonesia (Stracher et al., 2004). In eastern Kentucky alone, there are more than 30 coal-mine fires (Jenn O'Keefe, Morehead State University, personal communication, 2015), with hundreds burning in the United States and thousands worldwide (Stracher, 2007). Some of these fires have been burning for centuries, with observed flames as high as 20 m and temperatures exceeding 1,000° C (Stracher, 2004). Economic loss in China is estimated at US$125 to $250 million, and as much as 10 percent of the country's coal has been destroyed by these fires (Rosema et al., 1999; Voigt et al., 2004). The cost to extinguish the existing fires in the United States would be US$651 million (Stracher, 2004, 2007).

Coal fires may result in sinkholes, valleys, slump blocks, chemically altered rocks and minerals, paralavas, red clinker, fissures, gas vents, tars, and other thermochemical processes. Health issues related to these fires include carbon monoxide poisoning, arsenosis, fluorosis, bronchitis, stroke, lung cancer, pulmonary heart disease, and chronic obstructive pulmonary disease (Finkelman et al., 2002; Stracher et al., 2004; Pone et al., 2007).

Carbon dioxide and carbon monoxide, as well as many other constituents, are of concern in the evaluation of potential greenhouse gases. In China, the world's largest coal producer, it is estimated that as much as 3 percent of that country's annual CO_2 emissions

derive from coal fires (Cassells and van Genderen, 1995; Zhang and Kroonenberg, 1996). Total world CO_2 emissions from coal fires are not well understood, but extrapolating worldwide, total CO_2 emissions and coal losses may be several times as large.

Other potentially harmful coal-fire emissions include the C_1–C_{10} hydrocarbons; benzene, toluene, ethylbenzene, and the xylene isomers (BTEX); and polynuclear aromatic hydrocarbons (PAHs). BTEX compounds are known to be carcinogenic and PAHs are known to have carcinogenic, mutagenic, and teratogenic effects (Stracher et al., 2004; Pone et al., 2007; Zhao et al., 2008; Carras et al., 2009; Hower et al., 2009; O'Keefe et al., 2010, 2011; Engle et al., 2011, 2012b). Incomplete coal combustion, as often occurs in coal-mine fires, is conducive to formation of heavy (four or more ring) PAHs (Liu et al., 2001), which could be present in soil, air, groundwater, and surface water in the vicinity of fires.

Previous studies have established that coal fires are harmful to humans and the environment. This produces unique challenges for scientists, engineers, landowners, politicians, and other interested parties. Development of cost-effective methods for preserving, identifying, and extinguishing coal fires should continue to be developed. I focus on three aspects of coal fires, and then elaborate on future research, based upon the results. This dissertation is divided into three sections, with the following organizational structure:

In Chapter 1, reports on emissions, minerals, and tars from coal fires in different geologic regions are reviewed for a comparative analysis of coal-fire sampling methods and technologies. The goal is to review past works and list technologies used over time, noting qualitative and quantitative preference when applicable. Some instruments are preferred over others. Short-term and long-term sampling technologies, as of 2014, are discussed.

In Chapter 2, principal component analysis software is used to determine relationships between gases at eastern Kentucky coal fires. I hypothesize that (1) numerous variables outside of our control affect the interpretation of coal-fire emissions

(these will be outlined) and (2) there is a geochemical relationship between certain coal-fire emissions.

In Chapter 3, the analysis of volatile organics and other relevant constituents from groundwater, surface water, and soil near two active mine fires in eastern Kentucky—the Truman Shepherd fire (Knott and Floyd Counties) and the Lotts Creek fire (Perry County)—is discussed. Although most research on coal fires has been focused on emissions, published data on water and soil quality in areas affected by coal fires are scarce, especially with respect to volatile organics (BTEX and PAHs). The goal is to provide preliminary data on these mostly unknown elements of fires. I hypothesize that (1) coal fires contribute to localized soil and water contamination and (2) contaminant levels vary between the Truman Shepherd and Lotts Creek fires because of differences in landscape, geology, and other factors.

Hypotheses, objectives, and tasks are outlined below. This list will be revisited at the end of the dissertation.

Hypothesis	Objective	Task	Section
Scientists have used a variety of methods and technologies to quantify coal-fire data.	Review past works and list technologies used, noting qualitative and quantitative preference when applicable.	Review applicable literature and corroborate with experts in the field.	1
Numerous uncontrolled variables affect the interpretation of coal-fire emissions.	Identify and list uncontrolled coal-fire variables.	Review applicable literature and corroborate with experts in the field.	2a
Geochemical relationships between certain coal-fire gases indicate that incomplete combustion is occurring.	Use PCA to determine which coal-fire gases have strong relationships.	Collect gases at five eastern Kentucky coal fires (78 data points), then analyze using PCA to identify patterns.	2b
The Truman Shepherd and Lotts Creek coal fires contribute to soil and water contamination. There are discrepancies in pollution between these fires because of landscape differences and the excavation at Truman Shepherd.	Identify and define extent of soil and water contamination at Truman Shepherd and Lotts Creek.	Collect and analyze soil and water data around the Truman Shepherd and Lotts Creek fires.	3

1. Chapter 1 - Evolution of Coal-Fire Sampling Methodology

This chapter focuses on coal-fire emissions, minerals, and tars, and how technology used to collect such samples has evolved over a span of approximately 7 years.

1.1 Introduction

Emissions, minerals, and tars from coal fires in different geologic regions were collected by the Center for Applied Energy Research at the University of Kentucky, in collaboration with Morehead State University, East Georgia College, the University of Silesia (Poland), and the U.S. Geological Survey for a period of 6 years. A comparative analysis of coal-fire sampling methods was conducted. Items that are discussed include field and laboratory equipment and techniques, emission collection, and minerals and tar deposits near coal-fire vents.

1.2 Locations and Geology

The eastern Kentucky coal fires CAER scientists and their colleagues studied are geologically located in high-volatile A bituminous coals of the Breathitt Formation. The Tiptop fire (Hower et al., 2009) in Breathitt County is in the Middle Pennsylvanian Skyline coal bed. The Truman Shepherd fire (Upper Elkhorn coal zone) is in Floyd County, and the Ruth Mullins fire (Hazard No. 7 coal bed) is in Perry County (O'Keefe et al., 2010; Hower et al., 2011; Silva et al., 2011). Old Smokey (O'Keefe et al., 2011) is in the Broas coal bed (Hazard No. 9) in Floyd County. The Lotts Creek fire (Hower et al., 2012) is in the Hindman coal bed (Hazard No. 9) in Perry County.

Engle et al. (2011, 2012) investigated sub-bituminous coal fires in the Paleocene Fort Union Formation in the Powder River Basin, Wyoming. Fires in the Witbank and Sasolburg coalfields of South Africa were studied by Pone et al. (2007). Fabianska et al. (2013) studied coal fires in the upper and lower Silesian Basin of Poland. Other studies include the South Canyon Number 1 coal-mine fire in Glenwood Springs, Colorado (Stracher et al., 2004); the Emery Coal Field fire in Utah (Stracher et al., 2005), the Wuda coal fire of Inner Mongolia (Stracher et al., 2005), and coal combustion in the Helan Shan

Mountains of northern China (Stracher et al., 2014). Stracher and Carroll (2013) examined the Mulga gob fire in Alabama.

1.3 Objectives and Discussion

Sampling techniques for measuring coal-fire emissions, minerals, and tars have been researched and summarized for this chapter. The goal is to review past works and list technologies used, noting qualitative and quantitative preference when applicable. Coal-fire environments are potentially dangerous, and safety precautions should be taken against potentially harmful emissions by wearing a National Institute for Occupational Safety and Health–approved Multi Gas/Vapor Cartridge/Filter 60926 P100 fitted mask and using gloves for sampling. Table 1 indicates the parameters of interest.

Table 1: Measurements discussed in this chapter.

Short-Term Measurements	Long-Term Measurements
Temperature	Temperature (vertical and aerial)
Carbon monoxide	Carbon monoxide
Carbon dioxide	Magnetic surveys
Mercury	
Velocity	
Volatile organic compounds	
Tars	
Minerals	

1.4 Short-Term Techniques

"Short-term" refers to real-time measurements, whereas long-term refers to those recorded over several hours or days.

1.4.1 Gas Temperature and Velocity Measurements

Temperature measurements at the Tiptop fire were collected using a Vernier Software and Technology Thermocouple probe linked to a Texas Instruments Inc. T1-84 calculator in May 2008 and on January 15, 2009 (Hower et al., 2009). In later studies, an

infrared Digi-Sense probe was used to collect soil and air-temperature data (Engle et al., 2011, 2012; O'Keefe et al., 2011; Hower et al., 2013). An S-type Pitot tube attached to an FKT 1DP1A-SV Flow Kinetics flow meter was used to collect gas velocity information as well as temperature, humidity, and gas density data (O'Keefe et al., 2010, 2011). The "Long-Term Sampling Techniques" and "Other Sampling Techniques" sections of this chapter provide additional information about temperature measurements, including aerial temperature measurements discussed in the latter section.

1.4.2 Gas Collection and Composition Measurements

Carbon dioxide data were collected from the Tiptop fire (Hower et al., 2009) and the initial studies of the Ruth Mullins and Truman Shepherd fires (O'Keefe et al., 2010) with a CH-23501 Dräger tube. This glass tube contains a chemical reagent calibrated for measuring 0.1–6.0 percent (v/v) CO_2 within a temperature range of 0–30° C. Carbon monoxide data were obtained using a CH-25601 Dräger tube containing a chemical reagent calibrated for measuring 10–3,000 $\mu g/m^3$ within a temperature range of 0–50° C. O'Keefe et al. (2011) and Engle et al. (2011, 2012) used an Industrial Scientific MX6 iBrid gas detector for CO_2, H_2S, and CH, and CH_4 gas-vent flow measurements. O'Keefe (Morehead State University, personal communication, 2014) found that Dräger tube measurements do not accurately estimate CO_2 and CO concentrations in vent emissions and that errors using the tubes are as high as 25 percent. Therefore, the more-accurate iBrid instrument was used for additional gas measurements.

Engle et al. (2011, 2012) used thermal infrared imaging in conjunction with ground-based measurements to collect soil- and gas-vent data. Soil CO_2 data were acquired using a 3-L West Systems fluxmeter (accumulation chamber) equipped with a Li-820 Li-Cor nondispersive infrared gas analyzer, controlled with a handheld personal-digital assistant. Soil CO_2 diffusion was measured at the Ruth Mullins and Tiptop fires, but well-indurated sandstones in the overburden above burning coal limited most of the emissions to fractures.

1.4.3 Mercury Measurements

Mercury concentrations were measured at the Tiptop fire (Hower et al., 2009) and during initial sampling trips to the Ruth Mullins and Truman Shepherd fires (O'Keefe et al., 2010). At both locations, mercury concentrations at coal-fire gas vents were measured using an Arizona Instrument LLC Jerome 431-X mercury vapor analyzer with a sensitivity range of 3–999 $\mu g/m^3$ at temperatures up to 40° C. At the Tiptop fire, mercury concentrations were also measured by Hower et al. (2009), using a CH-23101 Dräger tube. Engle et al. (2011, 2012) used an RX-915 Ohio Lumex portable mercury analyzer in a study of Powder River Basin coal fires in Wyoming. The RX-915 was later used by Hower et al. (2013) at Truman Shepherd. O'Keefe et al. (in preparation) used the Ohio Lumex instrument at Ruth Mullins in eastern Kentucky and concluded that the Jerome instrument consistently overestimated mercury concentrations in previous studies.

1.4.4 Volatile Organic Compound Measurements

Volatile organic compounds were analyzed for gas samples collected at all of the fires studied in Kentucky (Hower et al., 2009, 2012; O'Keefe et al., 2011, Morehead State University, personal communication, 2014). The samples were collected in evacuated and electropolished, stainless-steel canisters that were supplied by and returned with the gas samples to the Rowland-Blake Group Laboratory, University of California–Irvine, for gas chromatographic analysis (Blake et al., 2011). Quality assurance and control procedures are described in Colman et al. (2001). The Rowland-Blake Group analyzed each gas sample for aliphatics (methane to nonane), aromatics (BTEX), and other carbon-bearing compounds (CO, CO_2, carbonyl sulfate, dimethylsulfide, and carbon disulfide).

1.4.5 Gas Velocity Measurements

An S-type Pitot tube attached to the Flow Kinetics flow meter mentioned above was first used to measure gas velocity from vents at the Truman Shepherd fire (O'Keefe et al., 2010). Pitot tubes are used in volcanology research (see, for example, Matsushima et al., 2003), but this was the first known use of a Pitot tube for coal fires in the United States. Litschke (2005) used a Pitot tube in a coal-fire study in Germany. The technique was used subsequently in the Powder River Basin (Engle et al., 2011, 2012), Old Smokey

(O'Keefe et al., 2011), Lotts Creek (Hower et al., 2012; J. Hower, CAER, personal communication, 2014), Truman Shepherd (Hower et al., 2013), and Ruth Mullins (Jenn O'Keefe, Morehead State University, personal communication, 2014) fires.

1.4.6 Tar Characterization

Emsbo-Mattingly and Stout (2010) examined the signatures of extractable semivolatile hydrocarbon tars from the Ruth Mullins coal fire in eastern Kentucky and compared them to a controlled-oven coal burn. The tars were characterized using a gas chromatography/flame ionization detector to measure C9–C44 hydrocarbons (Environmental Protection Agency Method 8015C) and gas chromatography/mass spectrometry using a modification of EPA Method 8270D (Environmental Protection Agency, 2014) to identify polycyclic aromatic hydrocarbons (PAHs) with two to seven rings, including parent and alkylated isomers and geochemical biomarkers (Stout and Emsbo-Mattingly, 2008). Thermal transformations affecting coal include temperature, oxygen concentrations, residence time, and catalytic surfaces. The primary extractable semivolatile hydrocarbons in the Ruth Mullins coal (Figure 1) are alkylated naphthalenes, plant waxes, and a wide- and late-eluting unresolved complex mixture. Diagrams "B" and "C" shown in Figure 1 were originally mislabeled by Emsbo-Mattingly and Stout (2011) as "carbonized coal." These have been corrected to "coal tar" in Figure 1. According to Emsbo-Mattingly and Stout (2011):

> The first sample (site 1) contains three- to six-ring pyrogenic PAHs and a late eluting UCM. The second sample (site 2) contains predominantly four- to six-ring PAHs and a late eluting UCM. The greater depletion of two- and three-ring PAHs in the site 2 compared to the site 1 sample indicates that the sample from site 2 experienced a greater degree of thermal stress than from site 1. The relative abundance of four- to six-ring PAHs in the carbonized coal from site 2 may reflect hotter temperature, longer residence time, or more exposure to catalytic surfaces leading to a greater degree of carbonization. Collectively, the source signatures of the extractable hydrocarbons in both carbonized subsurface coals and coal tars found at surface vents from the Perry County coal fire indicate the widespread presence of PAH-rich residues consistent with variably weathered coal tar. The variability in the coal-tar signatures observed at the vents likely reflects the sequential layering of less weathered and more weathered coal-tar residues. Alternatively, the existence of variously weathered coal tars may represent different mixtures of coal tar and condensates from older (cooked) and newer (leading edge) zones within the coal-fire area."

Tars from burning coal have also been described for the Powder River Basin in Wyoming (Engle et al., 2012) and the 2009–2010 Ruth Mullins fire (O'Keefe et al., in preparation).

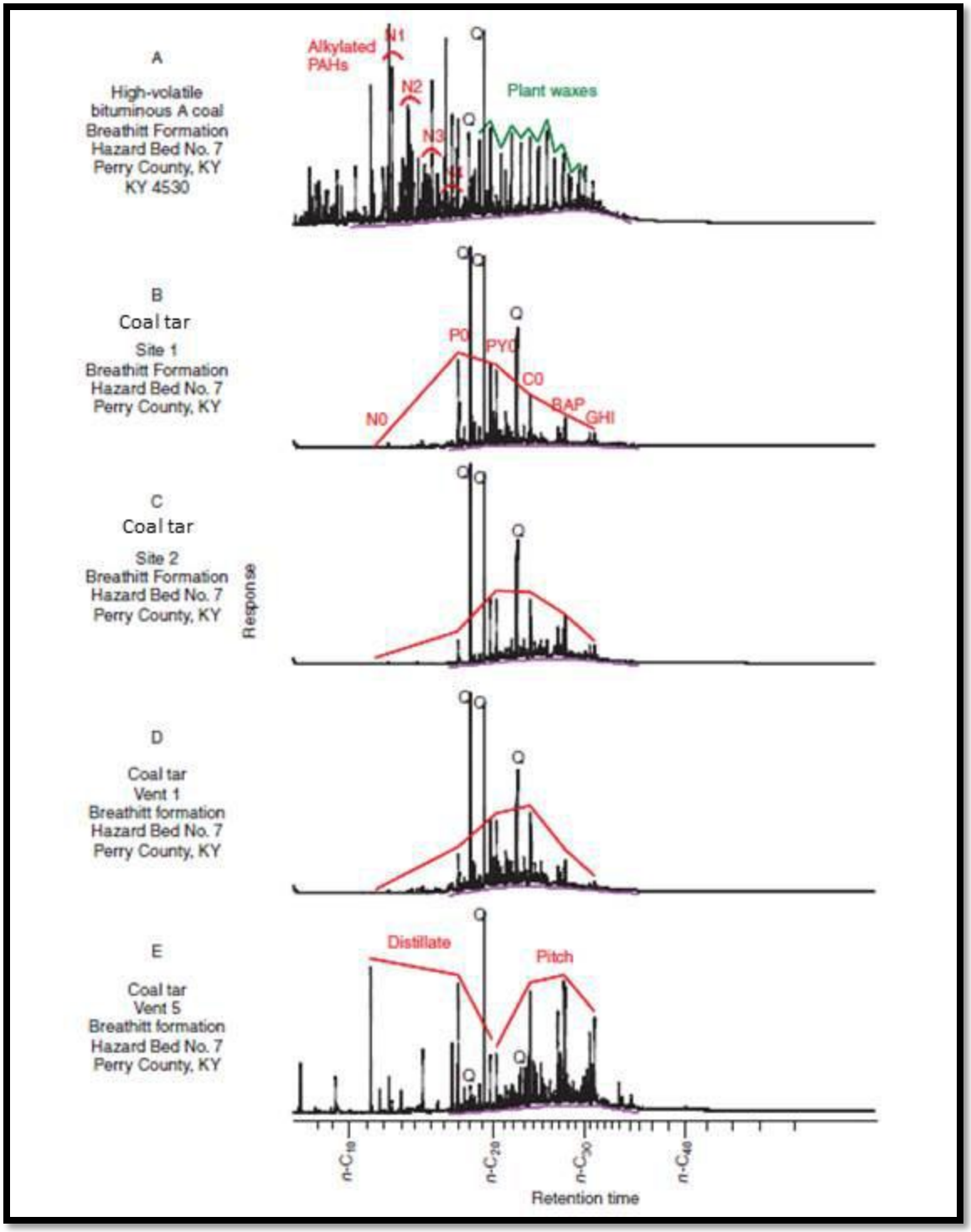

Figure 1: Fingerprints of coal and tar at the Ruth Mullins coal fire. Modified from Emsbo-Mattingly and Stout (2011), p. 194. See also Stout and Emsbo-Mattingly (2008).

1.4.7 Mineral Sampling and Analysis

Mineralization at coal-fire gas vents and fissures has not been commonly observed in eastern Kentucky, but it was found at the Ruth Mullins fire (Figure 2) and the Truman Shepherd fire. When minerals (or amorphous phases) nucleate in association with coal-fire gas, they do so by one of two possible thermochemical processes: (1) isochemical mineralization or (2) mass transfer mineralization; these processes may each be subdivided into specific nucleation mechanisms (Stracher, 2007).

In 2002, an experiment was conducted at an underground bituminous coal fire in East Kalimantan, Borneo, Indonesia (Stracher et al., 2011). Unglazed ceramic tiles were partially placed over gas vents in an attempt to "force" the gas to cool and nucleate minerals (Figure 2). Within 2 weeks after setting the tiles in place, minerals appeared on the sides of tiles placed over several adjacent vents, and creosote appeared on a tile placed over a different vent (Figure 3). The minerals were identified by X-ray diffraction as orthorhombic sulfur-8 and gypsum (Stracher, 2011; Stracher et al., 2013). The nucleation process may have occurred by mass transfer mineralization (Stracher, 2007), because unlike coal-fire gas, ceramic tile contains the calcium that occurs in the gypsum identified.

Figure 2: Mineralization on tree roots at the Ruth Mullins fire. The horizontal field of view is about 65 cm. Photograph by James C. Hower (2010).

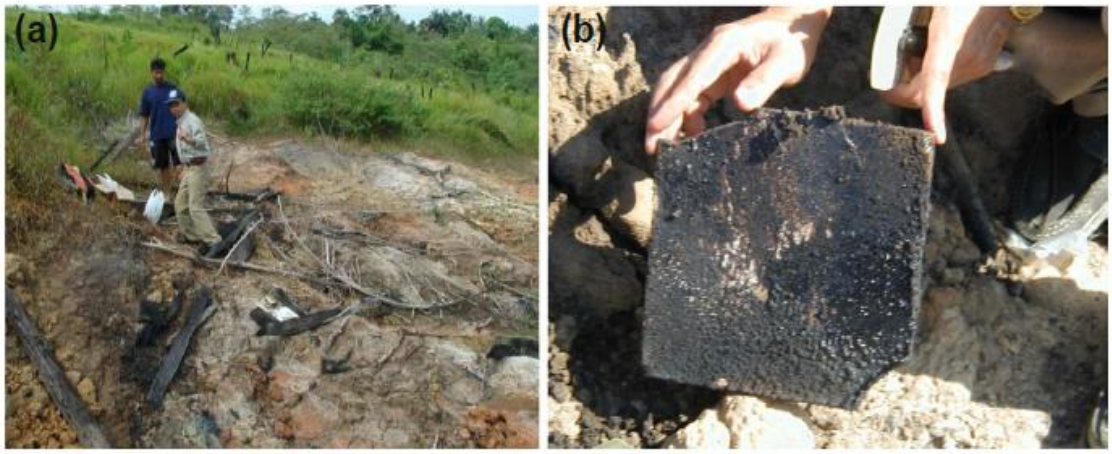

Figure 3: Unglazed ceramic tiles used at an underground Indonesian coal fire. (a) Asep Mulyana (tan clothing) places white tiles over gas vents in the Palarin District (fire site 2) of Samarinda County, East Kalimantan, Borneo. Orthorhombic sulfur-8 and gypsum nucleated on the tiles. (b) Creosote nucleated on a tile in the same district, but at fire site 1. From Stracher et al. (2013). Photographs by Alfred E. Whitehouse (2002).

At the Ruth Mullins fire (Silva et al., 2011), mineral samples were analyzed by optical mineralogy, X-ray diffraction, high-resolution transmission electron microscopy, high-resolution transmission electron microscope/energy dispersive X-ray spectrometry, selected area electron diffraction, microbeam diffraction, and fast Fourier transform. Similar methods were used by Silva et al. (2012) at the Ruth Mullins fire, but focused on carbon nanotubes. They concluded:

> The Ruth Mullins sooty carbon sampled on 19 August 2010 represents the only occurrence of this material found in multiple visits to the site over several years. It contains metal-bearing and halogenated carbon nanoparticles, onion-like structures with polyhedral and quasi-spherical morphology with hollow centers, and multi-walled nanotubes. In contrast to superficially similar soot from a coal-fired stoker boiler, fullerenes were not detected in the coal-fire soot. In addition to the carbon particles, Al–Si spheres with surficial metal precipitates, salammoniac, pickeringite with nanojarosite, and Cr- and Pb-bearing jarosite pseudomorphs after pyrite were associated with the deposit. High ^{15}N is consistent with the fractionation in the emission gases of NH_3 to NH_4 in salammoniac. ICP-MS analysis indicates that the carbon plus the crystalline and amorphous inorganics have high concentrations of Se, Pb, and Zn. LECO AMA 254 absorption spectrometer analysis yielded 5.68 ppm Hg, higher than any fly ash of Kentucky coals. Some of the Hg is associated with carbon nanotubes.

A study by Hower et al. (2013) of the Truman Shepherd fire in Kentucky included a discussion of mineralization associated with coal-fire gas. Mineral analysis was performed at Universidade Santiago de Compostela (Spain) on a Philips-type powder diffractometer fitted with a Philips PW1710 control unit, vertical Philips PW1820/00 goniometer, and FR590 Enraf Nonius generator. The instrument was equipped with a graphite diffracted-beam monochromator and copper radiation source ($\lambda(K\alpha 1) = 1.5406$ Å), operating at 40 kV and 30 mA.

Powder XRD analysis of mineral samples from Wyoming (Engle et al., 2012) was performed at the University of Georgia with a Bruker D8 Advance diffractometer using coradiation at 40 mA and 40 kV with a step size of 0.01° 2θ and a scan rate of 2.5° per minute, with a Lynx-eye 192 position sensitive detector. The samples were dry-mounted in aluminum holders and scanned at 8–60° 2θ with Cu Kα radiation. Among the combustion-related minerals found were gobbinsite ($Na_4[Ca,Mg,K_2]Al_6Si_{10}O_{32}\bullet 12H_2O$),

a zeolite; the ammonium sulfates mohrite-boussingaultite ($[NH_4]_2Fe[SO_4]_2 \cdot 6[H_2O]$-$[NH_4]_2Mg[SO_4]_2 \cdot 6[H_2O]$) (Parafiniuk and Kruszewski, 2009) and tschermigite ($NH_4AlSO_4 \cdot 12H_2O$); ammonium chlorides and ammonium sulfates; salammoniac (NH_4Cl) (Silva et al., 2011), and mascagnite ($[NH_4]_2SO_4$).

1.5 Long-Term Techniques

1.5.1 CO and Temperature Sampling and Measurement

At the Ruth Mullins fire, Hower et al. (2011) used a Dataq Instruments El-USB-CO Lascar data logger (maximum operating temperature of 50° C) for CO and temperature measurements (Figure 4). The "Tin Man" assemblage (Figure 5) was used to protect the equipment from rain and snow and to allow the collection end of the data logger to extend into the gas-vent emission.

Figure 4: The El-USB-CO (for CO) and the El-USB-TC (for temperature) Lascar data loggers for long-term measurements (Hower et al., 2011, 2013). Photograph by James C. Hower (2009).

Figure 5: Rachel Hatch holding the "Tin Man" assemblage (Hower et al., 2012). Photograph by James C. Hower (2009).

1.5.2 Truman Shepherd and Ruth Mullins Gas Temperature

In the Truman Shepherd study (Hower et al., 2013), the EL-USB-TC Lascar data logger coupled with the K-type thermocouple probe (temperature range up to 1,300° C) and the USB-PRO-N Lascar data logger, both housed in a PVC pipe assembly, were used to record temperatures at 1-minute intervals for a total of 22 days, 11 hours, and 49 minutes (32,859 data points for each instrument).

At the Ruth Mullins fire, the EL-USB-TC Lascar data loggers with a K-type thermocouple probe (temperature range up to 1,300° C) were used to record temperatures at 10-second intervals for 3 days and 1-minute intervals for 22 days (Hower et al., 2011).

1.5.3 Vertical Temperature Measurements at Lotts Creek

A new experimental apparatus was designed for the Lotts Creek fire (Hower et al., 2012). The assemblage consisted of five K-type thermocouple probes spaced at 1-meter intervals (capable of detecting a maximum temperature of 1,350° C with an accuracy of ±1° C), connected to EL-USB-TC Lascar data loggers sealed in a plastic bag in a side port of the "Tin Man"; this protected the data loggers from steam and coal-fire gas as well as from inclement weather. Each data logger was set to record temperatures at 1-minute intervals for more than 22 days.

1.6 Other Sampling Techniques

1.6.1 Aerial Temperature Measurements

Aerial thermal infrared has been used to detect locations of underground coal fires since the 1960's (Knuth et al., 1968; Prakash et al., 1995; Zhang et al., 2004). Engle et al. (2011, 2012) used TIR to observe select coal fires in Wyoming. An automated FLIR A320 camera (Test Equipment Connection, 2014) was mounted under the wing of an aircraft during predawn flights. Temperatures derived from TIR data are a function of land-surface emissivity. Fire area, perimeter, and surface temperature were estimated from the Wyoming study.

1.6.2 Gas Collection

An alternate method of collecting coal-fire gas samples used by Stracher (2007) at the Centralia Mine fire in Pennsylvania consisted of pumping the gas from vents and fissures with a hand or electric pump into Tedlar gas bags made by DuPont. This method proved inadequate, however, because gas chromatographic analysis of samples from the

same bags over a 2-week period revealed that the bags exchanged coal-fire gas with the atmosphere (Donald L. Blake to Glenn Stracher, personal communication, 2007).

Giggenbach fused-silica gas sampling bottles are used by some volcanologists to collect volcanic gas. Glenn B. Stracher has had several such bottles made by Glasscraft Scientific Glassblowing Ltd, Lower Hutt, New Zealand, but has not used them yet. I know of no one who has used these bottles to collect samples of coal-fire gas for analysis.

1.6.3 Magnetic Measurements

When heated above the Curie point, the magnetic moment realigns magnetite domains in the direction of Earth's magnetic field (Ide et al., 2011). Near Durango, Colorado, Ide et al. (2011) used magnetometer measurements to characterize a subsurface coal fire. Magnetometer surveys allow high-resolution areal mapping that differentiates among previously burned, currently burning, and unburned coal seam measurements. Ide et al. (2011) concluded that:

(1) Spatial variations in magnetic anomaly can be used to determine with relatively high resolution the locations of burned and cooled, actively combusting, and unburned regions.
(2) Filtering observed magnetic anomaly data to remove the effects of diurnal variations in Earth's magnetic field, effects of metal objects, and effects of alignment with the direction of the magnetic pole allow more straightforward interpretation of the results.
(3) Magnetometer observations at the North coal fire are consistent with all the other lines of physical measurements, and they offer much improved resolution of the burned and burning zones than do other available methods.
(4) Repeat surveys at the North coal fire indicate that results obtained are repeatable and that monitoring movement of the combustion front is possible.
(5) The use of magnetic anomaly measurements requires that the rocks heated by a subsurface fire contain sufficient magnetite.

Another study about coal fires using a magnetometer was conducted in North Dakota by Sternberg (2011). Conclusions from this study reveal that magnetics may help locate the boundary between an unburned coal seam and clinker. In addition, remnant magnetism in combustion metamorphic rocks may make them useful for determining paleomagnetic field directions.

1.7 Summary and Conclusions

1.7.1 Temperature Measurements

In early studies, short-term temperature measurements were collected using a Vernier thermocouple probe linked to a T1-84 calculator. This was eventually replaced by the more efficient Digi-Sense probe with a K-type thermocouple for the collection of soil and air temperature data. The S-Type Pitot tube attached to a Flow Kinetics FKT 1DP1A-SV flow meter also measures temperature as a correction parameter in the air flow calculation. For long-term temperature measurements, a Lascar EL-USB-TC datalogger coupled with a K-type thermocouple and a Lascar USB-PRO-N datalogger were used; both were housed in a PVC pipe assembly or in the "Tin Man" housing.

1.7.2 CO_2 Measurements

A Dräger CH-23501 detection tube was initially used to measure short-term CO_2 emissions. This was replaced by an Industrial Scientific MX6 iBrid combustion gas analyzer. In the Wyoming study, soil data were acquired using an accumulation chamber technique in which the flux chamber utilized a Li-Cor Li-820 non-dispersive infrared gas analyzer and a 3-L West Systems Chamber, both controlled by a handheld personal digital assistant.

1.7.3 CO Measurement

Early short-term CO data were obtained using a Dräger CH-25601 detection tube. This was replaced by an Industrial Scientific MX6 iBrid combustion gas analyzer. Long-

term measurements were collected via the Lascar El-USB-CO data loggers installed in the "Tin Man" assemblage.

1.7.4 Mercury Measurement

Mercury concentrations were originally measured using an Arizona Instruments Jerome 431-X Hg Vapor Analyzer and a Dräger CH-23101 detection tube. These were later replaced by an Ohio Lumex RX-915 Portable Mercury Analyzer (O'Keefe et al., in preparation).

1.7.5 Gas Velocity

An S-Type Pitot tube attached to a Flow Kinetics FKT 1DP1A-SV flow meter was used to measure gas velocity. This is a common instrument used in volcanology research, but studies noted herein are among the first to use the Pitot tube with coal fires.

1.7.6 Volatile Organic Compounds

Coal-fire gas samples were collected in electropolished, stainless steel, evacuated canisters. Constituents were analyzed by Rowland-Blake Group laboratory at the University of California–Irvine using a gas chromatograph system. The Rowland-Blake Group analyzed the gases for a full suite of simple carbon-bearing gases (i.e., CO, CO_2, carbonyl sulfate, dimethylsulfide, and carbon disulfide), aliphatic compounds (methane to nonane), and aromatics (benzene, toluene, ethylbenzene, and xylene).

1.7.7 Other Measurements

Mineral deposits and tars associated with coal fires have been analyzed by a wide variety of methods. Unglazed ceramic tiles (Stracher, 2011; Stracher et al., 2013) were successfully used to "force" coal-fire gas to nucleate orthorhombic sulfur-8 and gypsum.

In a Colorado study (Ide et al., 2011), a magnetometer was used to characterize a subsurface coal fire. A magnetometer was also used to characterize a coal-fire burn site in North Dakota (Sternberg, 2011). Magnetometer surveys are useful for high-resolution

areal mapping that differentiates among previously burned, currently burning, and unburned coal seams. Remnant magnetism revealed by these surveys, in combustion metamorphic rocks, may be useful for determining paleomagnetic field directions.

Aerial thermal infrared of coal fires in the Powder River Basin, Wyoming, utilized an automated FLIR A320 camera mounted under the wing of an aircraft during predawn flights. Temperatures derived from the data acquired are a function of land-surface emissivity. Fire area, perimeter, and temperature were estimated.

Tedlar gas bags, made by DuPont, were used by Stracher (2007) for collecting samples of coal-fire gas. They proved to be unreliable because gas chromatographic analysis revealed that the bags exchange coal-fire gas with the atmosphere. Giggenbach gas sampling bottles used by some volcanologists, made from fused silica, have not yet been used to collect samples of coal-fire gas.

The preferred short-term technologies are as follows: temperature = Digi-Sense probe with a K-type thermocouple (air and soil); CO_2 = Industrial Scientific MX6 iBrid combustion gas analyzer; CO = Industrial Scientific MX6 iBrid combustion gas analyzer; mercury = Ohio Lumex RX-915 portable mercury analyzer; velocity = S-type Pitot tube with a Flow Kinetics FKT 1DP1A-SV flow meter; and VOC's = electropolished, stainless steel, evacuated canisters. The only long-term technologies used were a Lascar EL-USB-TC datalogger with a K-type thermocouple for temperature and Lascar El-USB-CO dataloggers installed in the "Tin Man" assemblage for CO. See Table 2 for a comparison of short-term technologies and Table 3 for long-term technologies.

Table 2: Short-term technologies.

Constituent	Short-Term Technology Used (2007–2014)	Short-Term Technologies Preferred (2009–2014)
Temperature	Vernier thermocouple probe linked to a T1-84 calculator (air and soil) Digi-Sense probe with a K-type thermocouple (air and soil) (Ancillary) S-type Pitot tube with a Flow Kinetics FKT 1DP1A-SV flow meter (air)	Digi-Sense probe with a K-type thermocouple (air and soil)
CO_2	Dräger CH-23501 detection tube Industrial Scientific MX6 iBrid combustion gas analyzer Li-Cor Li-820 nondispersive IR gas analyzer and a 3-L West Systems Chamber	Industrial Scientific MX6 iBrid combustion gas analyzer
CO	Dräger CH-25601 detection tube Industrial Scientific MX6 iBrid combustion gas analyzer	Industrial Scientific MX6 iBrid combustion gas analyzer
Mercury	Arizona Instruments Jerome 431-X Hg vapor analyzer Dräger CH-23101 detection tube Ohio Lumex RX-915 Portable Mercury Analyzer	Ohio Lumex RX-915 portable mercury analyzer
Velocity	S-type Pitot tube attached to a Flow Kinetics FKT 1DP1A-SV flow meter	S-type Pitot tube with a Flow Kinetics FKT 1DP1A-SV flow meter
VOCs	Electropolished, stainless steel, evacuated canisters	Electropolished, stainless steel, evacuated canisters

Table 3: Long-term technologies.

Constituent	Long-Term Technology Used
Temperature	Lascar EL-USB-TC datalogger with a K-type thermocouple
CO_2	NA
CO	Lascar El-USB-CO dataloggers installed in the "Tin Man" assemblage
Mercury	NA
Velocity	NA
VOC's	NA

2. Chapter 2 - Comparing Coal-Fire Emissions

2.1 Introduction

Chapter 1 provides a review of technologies used to analyze the following coal fire parameters: T, velocity, CO_2, CO, mercury, VOCs, as well as other measurements. My preferred technologies were used to collect measurements for this part of the study.

The purpose of this section is to consider whether there are relationships between gaseous emissions, specifically in five Kentucky coal fires. The coal fires have similar coal rank, geology, and landscape, thereby reducing the number of uncontrolled variables. The remaining variables include:

- **Complete/Incomplete Combustion** – Complete combustion of coal does not occur until a temperature of 1,500° C is reached, and, in theory, only CO_2 and H_2O would be produced with complete combustion (Liu et al., 2001). Incomplete combustion is likely occurring in coal fires.
- **Fire Temperature/Size and Distance to Fire** – Kim (2007) found that coal-fire temperature is a major contributor to volatile organic emissions. Temperatures of soil and vents were collected at the eastern Kentucky fires, but actual fire temperatures are unknown because the sampling vents are variable and distances from the fires are uncertain.
- **Relative Humidity and Moisture in System** – Coal-fire CO and CO_2 emission ratios at a given time are related to relative humidity and amount of moisture in the system (Hower et al., 2013).
- **Geology, Geochemistry, and Age of Coal** – Variations in geology caused by the depositional environment in which coal formed may play a factor in combustion levels and emissions of coal fires. As coal fires migrate, they may encounter small-scale or large-scale changes in geology (faults, fractures, and other structures) and geochemistry. The presence of other coal seams near the fire, which are not the main source but secondary sources of emissions, may affect total emissions (Engle et al., 2012). The age of the coal and the associated nature of the plant communities (coal type) may also influence the nature of burn. In

theory, the inconsistencies related to this variable have been reduced by sampling gases originating from coals with similar ages, ranks, and types.

- **Condition of the Mine** (in mine fires) – Collapses and other changes may occur in coal-mine fires, resulting in precipitous changes in the fire. Because of this, air flow may vary, resulting in changes in fire dynamics.
- **Sampling Times** – Results vary depending on the time of day of sampling. Coal fires are subject to breathing cycles (Hower et al., 2009, 2013; O'Keefe et al., 2010, 2011). Samples must be collected at the appropriate time to get consistent results.
- **Sampling Equipment and Human Error –** As with any sampling, technology and human error can be the source of confusing data.

2.2 Methodology

Relative humidity; barometric pressure; density; flow rate; the flux ($mg/s/m^2$) of CH_4, CO_2, CO, and H_2S; and temperature were measured at several eastern Kentucky fires (Appendix I). An infrared Digi-Sense probe was used to collect soil and air-temperature data (Engle et al., 2011, 2012; O'Keefe et al., 2011; Hower et al., 2013). An S-type Pitot tube attached to an FKT 1DP1A-SV Flow Kinetics flow meter was used to measure gas velocity, temperature, humidity, and gas density at Old Smokey (O'Keefe et al., 2011), Lotts Creek (Hower et al., 2012), Truman Shepherd (Hower et al., 2013) coal fires, and for the 2009–2010 Tip Top and Ruth Mullins studies (Jenn O'Keefe, Morehead State University, personal communication, 2014). An Industrial Scientific MX6 iBrid gas detector was used to measure CO, CO_2, H_2S, and CH_4 concentrations at the same fires. Each reported measurement is the average of at least five individual Pitot tube measurements and five iBrid gas measurements (collected on the same day). For each instrument, the measurements were taken at different locations across the cross-sectional area of the vent. To the extent possible, both sets of measurements were taken at the same five spots.

For 78 data points sampled (several vents at each coal fire) over a period of 4 years, JMP version 10 (SAS, Cary, N.C.) software was used to disaggregate the data for principal component analysis. PCA is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components.

2.3 Results and Discussion

For the PCA analysis, the built-in relationships between the parameters must be considered. Most important, the gas flow measured by the Pitot tube is corrected by the instrument for the gas temperature (T), gas density (ρ), relative humidity, and barometric pressure. In turn, the gas-flow parameters are inherently part of the gas-flux calculation.

Figure 6 is the PCA interpretation of all eastern Kentucky coal-fire data (see Appendix I), based on the following parameters: relative humidity; barometric pressure; density; flow rate; the flux (mg/s/m^2) of CH_4, CO_2, CO, and H_2S; and T. The parameters are organized by quadrant. Parameter proximity within each quadrant indicates the degree of coal-fire parameter relationship. Selected parameters with strong relationships will be discussed individually later in this section. Parameters in opposite quadrants indicate that there are inverse relationships.

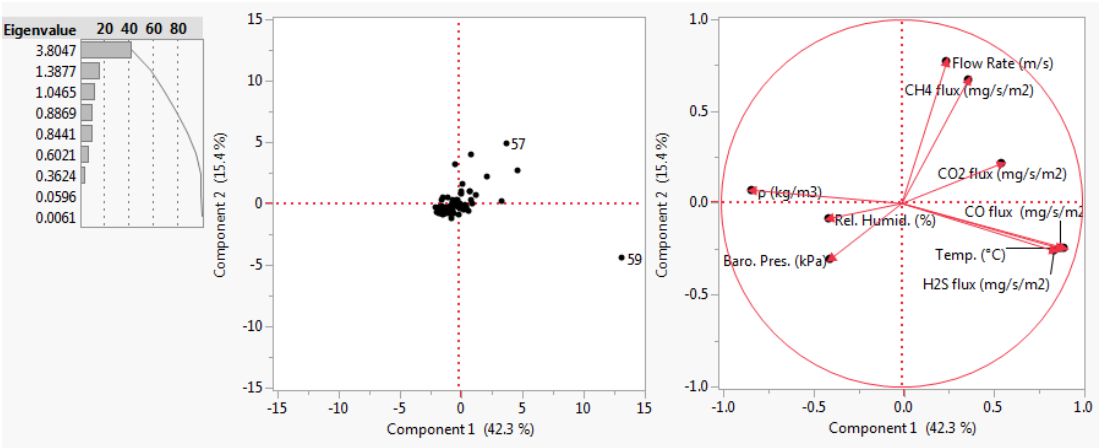

Figure 6: Principal component analysis for all Kentucky fires.

Datapoint 59 (vent 7 at Lotts Creek, measured February 24, 2012) may be anomalously high because of extremely high temperatures, but not in the sense that the data are erroneous. Rather, the high temperature at point 59 is a function of the proximity to the active fire. The datapoint, although valid, is problematic because no other datapoint is within 100° C of it. Therefore, as a lone, extreme datapoint, it has an outsized influence on the correlations. Vent 7 was not active a few months later during the July 2012 sampling [this is not the first time these fire movements have been noted in coal-fire literature (Hower et al., 2012)]. The fire intensified abruptly in May 2012 but was extinct by the time of the July 2012 measurements. Because of this, separate analyses were run excluding datapoint 59 (Figure 7) as well as datapoint 57, which is vent 3 at Lotts Creek (Figure 8). Datapoint 57 was excluded in the third analysis because it was also a potential outlier.

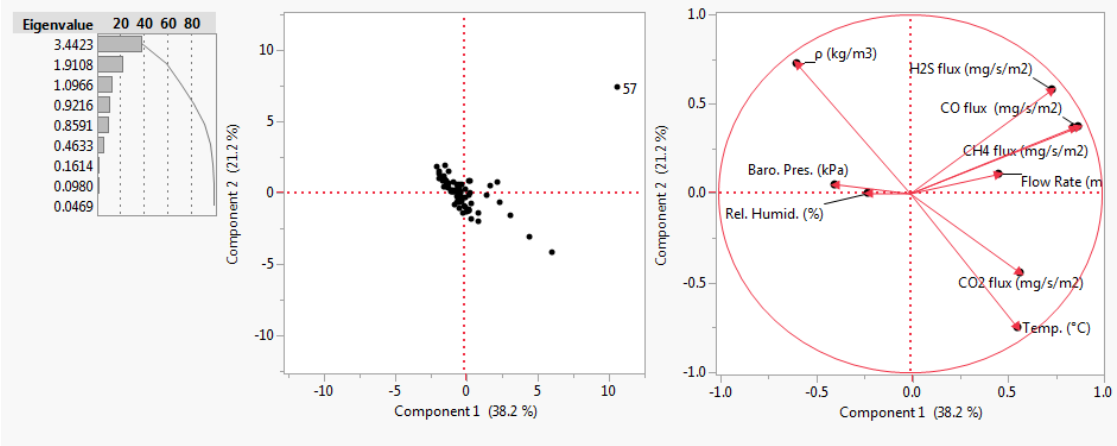

Figure 7: Principal component analysis for Kentucky fires, excluding data point 59.

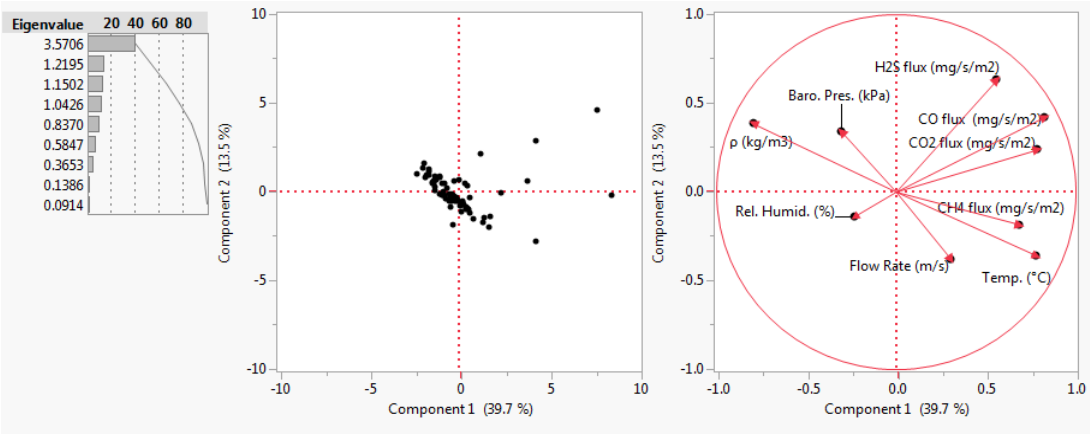

Figure 8: Principal component analysis for Kentucky fires, excluding data points 57 and 59.

Visual inspection of the plots reveals relationships between parameters, but squared multiple-correlation coefficient (R^2) calculations were used to more accurately determine the correlation strength between the noted parameters. In theory, R^2 values work well if sufficient data points are available throughout the data set. When there are a number of points far outside the mean, or data sets are inconsistent, R^2 is suspect, however.

In Figure 6, T, CO, and H_2S are very close together in quadrant 2, indicating strong relationships. Correlation between T and CO has an R^2 of 0.570. H_2S flux versus CO flux has an R^2 of 0.979, indicating an excellent correlation, and the R^2 of H_2S versus T = 0.510. The R^2 of CO_2 versus T = 0.227. All other parameters' R^2 values are below 0.1 (Appendix II). Data point 59 (vent 7 at Lotts Creek) for CO flux, the only value in the 12,000 mg/s/m^2 range, significantly controls the R^2 calculations, however. With the exclusion of this data point, the PCA analysis changes significantly (Figure 7). Temperature is now in a separate quadrant from CO and H_2S, and CO, CH_4, and H_2S are more closely related. The correlation between T and CO flux has an R^2 value of 0.045, a significant change from the 0.570 R^2 value cited above. H_2S flux versus CO flux has an R^2 of 0.799 (though this is a decrease from the 0.979 R^2 value above, it is still a good

correlation). The H_2S versus T value has an R^2 of 0.001, which is a dramatic shift from the previous R^2 of 0.510. CH_4 flux versus CO flux has an R^2 value of 0.744 instead of the previous value of 0.052, which is a significant improvement in the correlation. CH_4 versus H_2S also improved, with an R^2 of 0.653. Other comparisons have R^2 less than 0.1. Without point 59, the maximum CO flux is approximately 3,300 mg/s/m^2 instead of the 12,000 mg/s/m^2 range, which perhaps provides a more accurate R^2 value. The removal of this data point significantly changed the R^2 calculations with respect to T versus CO flux and CH_4 flux versus CO flux. A third analysis was run removing the top two data points, 59 and 57, both of which are Lotts Creek vents (Figure 8). CO versus H_2S has an R^2 value of 0.449, which is lower than the previous two values, but still significant; the CO versus CH_4 $R^2 = 0.333$, and CO versus CO_2 showed a significant increase to $R^2 = 0.501$. CO_2 versus T had an R^2 of 0.266, which is similar to the previous measurements, and CH_4 versus T increased to $R^2 = 0.226$.

As noted above, in Figure 1, CO, H_2S, and gas temperature are closely aligned in the PCA plot. Some consideration of the validity of this relationship is necessary in order to properly discuss the results. Overall, CO, CO_2, CH_4, and a wide range of volatile organic (including BTEX) gases are known to be products of coal fires (Stracher et al., 2004; Pone et al., 2007; Zhao et al., 2008; Carras et al., 2009; Hower et al., 2009; O'Keefe et al., 2010, 2011; Engle et al., 2011, 2012). The intensity of combustion should be a primary factor in determining CO versus CO_2 proportions in the exhaust gases. Typically, underground fires should be marked by oxygen-lean conditions, under which low-T combustion occurs (Liu et al., 2001). This favors formation of CO, H_2S, and VOC and BTEX gases over CO_2. Measurement of T is complicated by unknown factors such as the distance to the fire; the presence of obstacles, including collapsed passages; and the nature of the material being burned. Because the fires in this study are primarily in abandoned coal mines, most of the burning material is assumed to be coal, but the possibility that wooden roof supports, rags, and other combustible material left in the mine are also burning cannot be discounted. As such, the T of the fire cannot be directly measured; temperature can only be acquired at the outlet of the vent.

Overall, CO flux versus H_2S flux is by far the strongest relationship between the gas fluxes (Appendix II). As CO flux increases, H_2S flux increases. With incomplete combustion, which is largely controlled by temperature, CO and H_2S levels are higher than with complete combustion. With more complete combustion, CO_2 would form along with steam and SO_2.

2.4 Conclusions

There are a multitude of coal-fire variables, making these gases difficult to interpret; variables include sampling distance from the fire, moisture in the system, coal geology, mine condition, and sampling times. The possibility that multiple fires are burning at a single location cannot be discounted.

Seventy-eight data points were sampled (several vents at each coal fire) over a period of 4 years at five Kentucky coal fire locations. Because of the high number of data points, PCA software was used to calculate R^2 values. In the first analysis, CO flux versus H_2S flux is by far the strongest relationship (with T as a control), indicating a range of incomplete combustion.

Two additional analyses were run excluding data point 59 (vent 7 at Lotts Creek, which was relatively hot, presumably from proximity to the coal fire), and data point 57 (vent 3 at Lotts Creek). When these data points are removed from the data set, some R^2 values vary significantly, though the relationship between CO flux versus H_2S flux remains strong (Appendix II).

The relatively high levels of CO and H_2S present (Appendix I) indicate that a range of incomplete combustion is occurring. Because of this, there may be hydrocarbons in soil and water at Lotts Creek and Truman Shepherd. Chapter 3 explores that hypothesis.

3. Chapter 3 - Water and Soil Quality in Coal-Fire Regions

3.1 Introduction

Though a small number of coal-fire studies have measured BTEX and PAH soil contamination from fires (Stracher et al., 2007; Engle et al., 2012a), there is apparently no literature specifically on the detrimental impacts of coal-mine fires on groundwater. Numerous underground coal gasification studies have been conducted, however, and data have been collected on groundwater contamination from coal combustion. Underground coal gasification is the partial oxidation of coal in place (in situ) in the presence of gasifying agents such as air or oxygen and steam, and the withdrawal of the gaseous products through production wells (Ahern and Frazier, 1982). Two vertical wells are drilled into the desired coal seam a short distance apart (as much as 30 m), enhancing the permeability of the coal seam between the two wells by reverse combustion or directional drilling, igniting the coal at the bottom of one well, injecting a large volume of air or oxygen and steam, and recovering the gaseous products through the other well (Mead et al., 1979). A more recent method of determining underground coal gasification has evolved, in which in-seam boreholes are drilled using technology adapted from oil and gas production that can move the injection point during the process.

3.2 Background Information — Underground Coal Gasification

Ahern and Frazier (1982) thoroughly reviewed more than 300 underground coal gasification projects and found that the most complete studies focusing on impacts to groundwater are Hoe Creek I and Hoe Creek II in northeastern Wyoming; reports on Princetown I (West Virginia), Hanna III (Wyoming), and Fairfield, Big Brown, and Tennessee Colony (Texas) also contain pertinent information. Relevant information from these studies is summarized in Table 4.

Table 4: Comparison of relevant underground coal gasification data (modified from Ahern and Frazier, 1982).

Name	Hoe Creek I	Hoe Creek II	Hanna III	Princetown I	Fairfield	Big Brown	Tennessee Colony
Location	Wyoming	Wyoming	Wyoming	West Virginia	Texas	Texas	Texas
Year	1976	1977	1977	1979	1976	NA	1978–1979
Metric Tons of Coal Gasified	118	2,250	2,585	318	NA	NA	192
Coal Rank	Sub-bituminous	Sub-bituminous	Sub-bituminous	Bituminous	Lignite	Lignite	Lignite
Number of Monitoring Wells	11	14	12	NA	10	NA	NA
Test Duration in Days	11	58	38	12	26	NA	207
Length of Monitoring (Months)	25	9	NA	>12	12	24	13
Groundwater Flow (m/yr)	2	NA	NA	NA	<1	NA	NA
Maximum Groundwater Contamination Distance (m)	33	NA	NA	21	None; low groundwater velocity	NA	NA

In the first Hoe Creek study (Hoe Creek I), 11 monitoring wells were drilled into the coal aquifer. The frequency of sample collection was 3 days, 83 days, 183 days, and several other unspecified times 2 years after the burn. Approximately 70 inorganic and more than 250 organic species were analyzed. Ammonium, boron, calcium bromide, lithium cyanide, magnesium sulfate, potassium, and phenols all increased five-fold over background values. Outside of the burn area, several other constituents increased five-fold over baseline values. The constituents were barium, lead, dissolved organic carbon, and volatile organics (particularly benzene, toluene, xylene, and naphthalene). Some volatile species exhibited higher concentrations at distances of 12 to 30 m from the burn zone. Most of the changes occurred within 3 meters of the burn zone and were independent of direction. Boron, calcium, lithium, magnesium, zinc, ammonium, sulfate, and total dissolved solids increased over time at one monitoring well located 3.5 meters from the burn zone, probably because of the movement of contaminated groundwater out of the burn zone. Several other constituents (barium, cyanide, iron, and phenols) peaked

early and then dropped off to near-baseline values by the end of the monitoring period (Campbell et al., 1978a, 1979; Mead et al., 1977, 1978a, b, 1979a, b, 1980a, b; Stephens and Hill, 1978).

At Hoe Creek II, 14 monitoring wells were drilled into the coal or overlying aquifer. Water-quality samples were collected before, during, and several times after the burn. Results from Hoe Creek II were similar to those from Hoe Creek I. Phenols increased at both Hoe Creek I and Hoe Creek II, but they reached higher levels at Hoe Creek I. Phenol concentrations at Hoe Creek II were higher just outside the burn zone rather than inside, whereas the opposite occurred at Hoe Creek I. Also, conductivity and pH were lower in the burn zone of Hoe Creek II. The factors that may have caused these differences were (1) varied permeability, (2) coal-gasification dissimilarity, (3) different monitoring-well placement, or (4) possible aquifer interconnection from a roof collapse at Hoe Creek II (Mead et al., 1977, 1978a, b, c, 1979a, b, 1980, Stephens and Hill, 1978).

Hanna III water quality was monitored before, during, and after operation through the 12 wells completed into the coal seam or overlying aquifer. Field measurements were made for pH, temperature, and specific conductance, and laboratory analyses were carried out for approximately 30 inorganic constituents and total organic carbon. Baseline water quality at this location is intermittent. Sodium and total dissolved solids increased up to 1 year after gasification, whereas sulfate and chloride decreased in all wells. During gasification, conductance and temperature increased over baseline values in both the coal aquifer and overlying aquifer (Pellizzari et al., 1978; Virgona, 1978; Virgona et al., 1978).

The Pricetown study involved an unspecified number of wells and stream stations; the wells were drilled into the coal aquifer and overlying aquifers. Changes in water quality were detected as much as 20 meters from the burn zone. Constituents that increased over background were hardness, iron, zinc, boron, sulfate, phenols, cresols, naphthalene, benzopyrene, and chrysene/benz(a)anthracene, whereas pH decreased. A ruptured casing and fracturing may have engendered the migration of volatile species to the surface (Tharnau and Bates, 1980; Werner et al., 1980).

A total of 50 wells were drilled at the Fairfield location, four of which were in the coal seam. The monitoring timeline was before the experiment, at the end of gasification, and 1 year post-gasification. Temperature, pH, and specific conductance were field-analyzed, and ammonium, sulfate, phenols, and other unspecified constituents were analyzed in the laboratory. All monitored constituents increased during gasification and decreased with time afterward. Phenols were the principal organic species produced, but increased amounts of 2-ring and 3-ring PAHs were also found, especially in burn-cavity waters after underground coal gasification. Fairfield had low groundwater velocities; perhaps this is the reason no plume of phenols was noted extending downgradient from the burn zone. Groundwater velocities were estimated at less than 1 meter per year (Itz and Oliver, 1977; Humenick et al., 1978; Humenick and Novak, 1978; Mattox and Humenick, 1979).

The Tennessee Colony site was monitored pre-and post-coal gasification, and data were collected up to 13 months after gasification. Constituents that increased over baseline levels were calcium, zinc, iron, pH, magnesium ammonia, manganese, sulfate, mercury, phenols, boron, alkalinity, and sodium. Total organic carbon decreased over the same period (Humenick and Novak, 1978; Mattox and Humenick, 1979; Grant and Haney, 1980; Edgar, 1981).

The Big Brown test was monitored for approximately 2 years after gasification. The constituents produced by gasification were similar to those produced at the Tennessee Colony site. Sulfate, phenols, and ammonia decreased to near-baseline values after 700 days (Grant and Haney, 1980).

Below is a summary of relevant conclusions (Ahern and Frazier, 1982):

- **Computer models** indicate that groundwater velocity is the most important variable in chemical migration in underground coal gasification; groundwater velocity and the initial source concentration had the greatest effect on peak concentration and plume width (this is important because primary hydraulic conductivity in the current study is very low).
- **The quality of information in underground coal gasification tests** is an important factor to consider. A real difference in data may result from different

(1) gasification techniques, (2) coal rank, (3) hydrogeology, or (4) baseline water quality. An apparent difference may occur because of (1) different sampling techniques or (2) laboratory analytical methods.

- **High pressures and temperatures** ward off water from the underground coal gasification burn cavity but force volatile and semivolatile species out of the burn cavity and into the surrounding strata, causing significant groundwater-quality changes.
- **Organics –** (1) Dissolved and total organic carbon concentrations increase dramatically as much as 30 meters from the burn cavity, (2) movement occurs outward in all directions, primarily through coal fractures, (3) pressures attained during combustion and fracture permeability probably determine the distances traveled by volatile organic species, (4) phenols and cresols appear in high concentrations in the surrounding strata during combustion, and (5) benzene, toluene, xylene, and naphthalene also increase many times over baseline levels. Most of the nonvolatile organic species in the groundwater appear to originate in a thin char ring around the burn cavity. Phenol concentrations in groundwater within this ring tend to be the highest found at underground coal gasification sites. Naphthalene is found principally in groundwaters within this ring; benzene, toluene, and xylene typically reach their highest concentrations in these waters.
- **Inorganics –** (1) Volatile inorganic species exhibit increasing concentrations during combustion caused by movement of volatile species out of the burn cavity, (2) ammonia and methane are produced during pyrolysis and have been detected in high concentrations in the surrounding strata, and (3) hydrogen cyanide (a volatile species formed from the reaction of ammonia, methane, and other organic species) move out of the burn cavity and yield high cyanide concentrations in surrounding strata. Carbon dioxide and hydrogen gas, produced by pyrolysis of coal, are forced out of the burn cavity as far as 30 meters into the surrounding strata. The increased concentrations of these gases shift chemical equilibria and cause the dissolution of calcium, magnesium, iron, lead, and other cations that are present in the coal and whose solubility is a function of pH and carbon dioxide

concentrations. Increased temperatures from combustion may further influence the solubility of these nonvolatile inorganic species.

- **Transport mechanisms –** Two transport mechanisms dominate after underground coal gasification: convective mixing, which distributes species in a relatively small area around the burn cavity, and transport by regional groundwater movement, which causes a plume of altered water quality downgradient. Underground coal gasification (perhaps as well as coal-mine fires) can change regional flow patterns if roof collapse or extensive fracturing occurs. Convective mixing is most important for a few months after underground coal gasification, whereas regional transport persists over much longer periods.
- **Reduction of concentrations –** (1) Concentrations for most species generated during underground coal gasification decrease rapidly with **time** and **distance** from the burn cavity (Figure 9). Time and distance are by far the most important variables. (2) Leachate concentrations from ash produced during underground coal gasification decrease with time. Perhaps the decrease in calcium, sulfate, and some heavy metals with time is caused by a decrease in source concentrations. (3) Movement of constituents that sorb (Figure 10) away from the burn cavity will be strongly restricted by sorption, as long as sorption sites remain available on the solid materials.

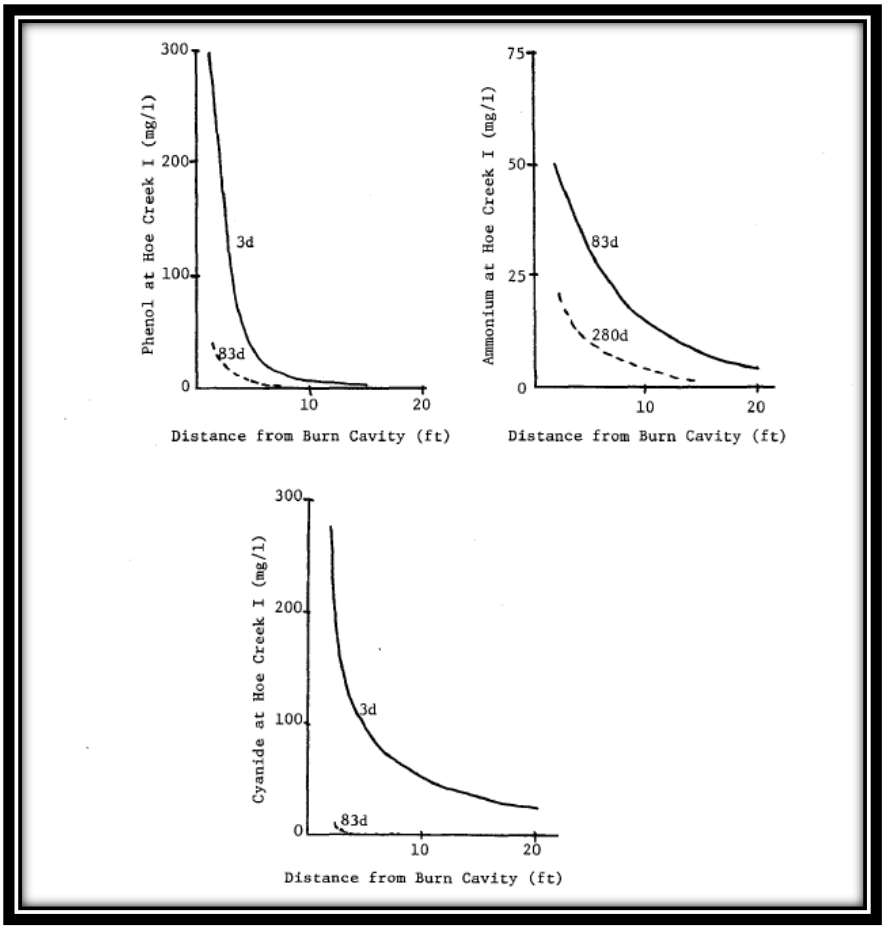

Figure 9: Concentrations as a function of time and distance at Hoe Creek I. From Campbell et al. (1979). 1 foot = 0.3048 m.

Species That Strongly Sorb	Species That Do Not Sorb
Ammonium	Calcium
Cadmium	Bromide
Lead	Chloride
Manganese	Selenium
Zinc	Sulfate
Phenols	
Naphthol	
PAHs	

Figure 10: Underground coal gasification species that sorb. After Ahern and Frazier (1982).

- **Other considerations –** Attenuation by dilution is much greater if flow occurs through fractures than through a homogeneous medium. Quantitative water-quality changes are not as consistent as qualitative changes. The maximum concentrations of underground coal gasification constituents vary tremendously, although differences in sampling time and sampling distance may account for the discrepancies. Collecting samples just a meter away from each other (relative to the burn cavity) makes a significant difference in concentration (Figure 9).

Few locations thoroughly studied PAHs specifically, but Ahern and Frazier (1982) concluded that the extent of groundwater contamination in all of the underground coal gasification studies was contained within a 33-meter radius around the burn cavity, and most were contained within a much narrower zone. Within this region of contamination, most constituents rapidly decrease in concentration because of sorption, dilution, biodegradation, and possibly other physicochemical processes. A better understanding of groundwater flow at underground coal gasification areas will be key to understanding the variation in geochemical parameters. The question remains, however: Are underground coal gasification sites representative of coal-mine fires? An attempt will be made to answer that question, but requisite background information and discussion will first be provided.

3.3 Natural Attenuation Processes

As concluded in the underground coal gasification studies, multiple natural processes have the potential to decrease BTEX and PAH levels in soil and water in coal-fire environments (Figure 11). A variety of physical, chemical, and biological processes can, under favorable conditions, reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater (Fetter, 1999). These processes include biodegradation, sorption, volatilization, chemical reactions, and dispersion/dilution.

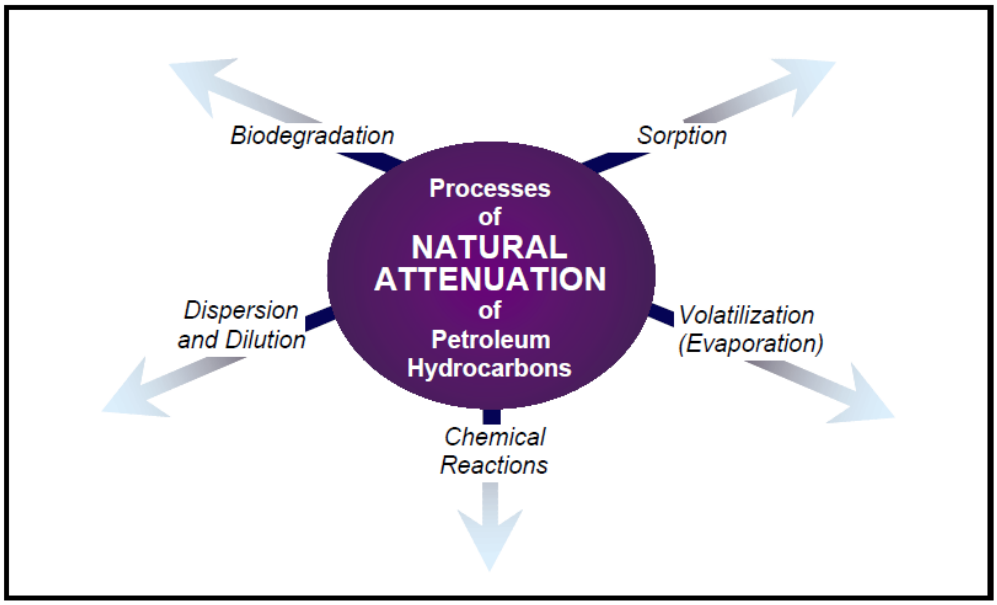

Figure 11: Processes of natural attenuation of petroleum hydrocarbons (Environmental Protection Agency, 1999).

The processes shown in Figure 11 are placed into two categories: nondestructive and destructive. Processes that result only in reducing the concentration of contaminants, and not the actual mass, are termed nondestructive, and include dispersion, sorption, and volatilization. Destructive processes, such as biodegradation and abiotic degradation (e.g., hydrolysis), result in an actual reduction in the mass of contaminants (Weidemeier et al., 1999). Four of these processes are briefly discussed below.

Biodegradation is the change in form of compounds carried out by living creatures such as microorganisms (Environmental Protection Agency, 1999). It is the

most important (and usually preferred) attenuation mechanism because it is the only natural process that results in actual reduction in the mass of petroleum hydrocarbon contamination (Environmental Protection Agency, 2004). In aerobic biodegradation, oxygen is consumed, resulting in anaerobic conditions in the core of the plume. The anaerobic zone (Figure 12) is typically more extensive than the aerobic zone because of (1) the rapid depletion of oxygen, (2) the low rate of oxygen replacement, and (3) the abundance of anaerobic electron acceptors (nitrate, sulfate, ferric iron, manganese, and carbon dioxide) relative to dissolved oxygen (Weidemeier et al., 1999). For this reason, anaerobic biodegradation is typically the dominant process. For both aerobic and anaerobic processes, the rate of contaminant degradation is limited by the rate of supply of the electron acceptor, not the rate of utilization of the electron acceptor by the microorganisms (Environmental Protection Agency, 2004). One factor is soil permeability. Soils that are relatively permeable, with a hydraulic conductivity of about 0.3 meters/day or greater, allow transfer of oxygen to subsurface soils, where the microorganisms are degrading the petroleum constituents. More discussion on this and how to derive calculations based upon soil type is found in Environmental Protection Agency (2004). In coal fires, there are challenges with this concept, however (discussed in the summary).

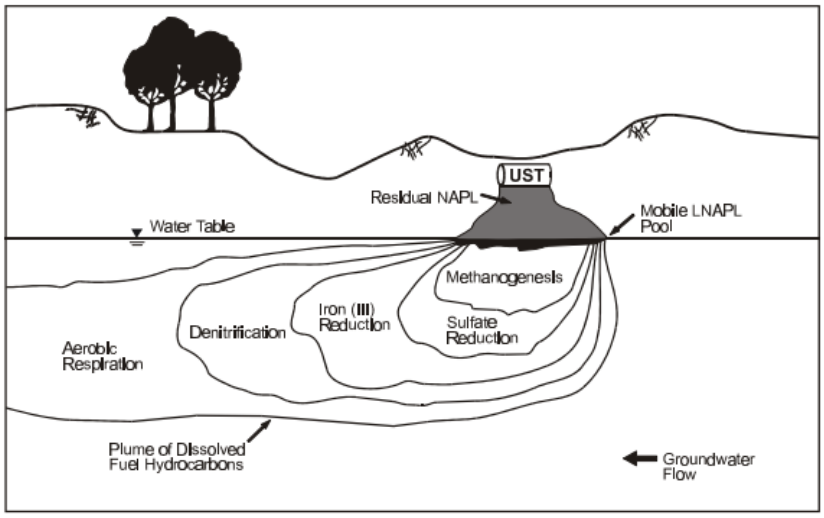

Figure 12: Contamination zones from a petroleum leak (Environmental Protection Agency, 2004).

Sorption is the process by which one substance becomes attached to another. Sorption to sand, silt, clay, and organic matter may occur from volatilization or by groundwater transport, thereby slowing or stopping the movement of contaminants (Figure 13). This process may reduce the distance the contaminant would have otherwise traveled (Environmental Protection Agency, 1999). In a comprehensive review of more than 300 underground coal gasification studies, Ahern and Frazier (1982) concluded that movement of contaminants that sorb (e.g., PAHs) away from the burn cavity is strongly restricted by sorption, as long as sorption capacity on solid materials has not been reached.

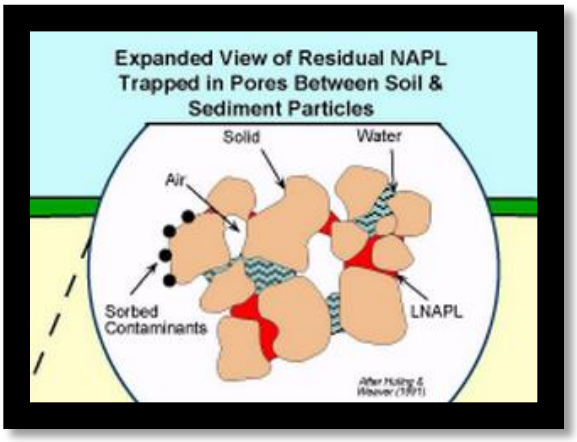

Figure 13: Diagram of sorption (Environmental Protection Agency, 1999).

In water, as dissolved contaminants are transported away from the source area, concentrations will decrease with distance because of dilution and dispersion. In soil, hydrocarbons disperse from the effects of gravity and capillary forces (suction). Contaminant concentrations may eventually decrease to levels that are no longer harmful to humans and the environment (Environmental Protection Agency, 1999), but contaminant mass is not reduced. In underground coal gasification studies, attenuation by dilution is reported to be much greater if flow occurs through fractures than through a homogeneous medium (Ahern and Frazier, 1982).

Volatilization is the evaporation of contaminants from groundwater or soil by transfer to the gaseous phase. In general, volatilization accounts for about 5 to 10 percent of the total mass loss of benzene at a typical site, with most of the remaining mass loss

the result of biodegradation (McAllister, 1994). For less volatile contaminants, the expected mass loss from volatilization is even lower.

The following analyses can determine whether these attenuation processes are occurring; they are organized based upon the medium:

- Soil: BTEX and PAH, pH, soil moisture, soil organic carbon, temperature, electron acceptors (dissolved oxygen, nitrate, ferric iron, manganese hydroxide, sulfate, and carbon dioxide), methane, sometimes hydrogen, as well as the microbes themselves (Environmental Protection Agency, 2004).
- Water: BTEX and PAH, pH, temperature, electron acceptors (dissolved oxygen, nitrate, ferric iron, manganese, sulfate, and carbon dioxide) (Environmental Protection Agency, 2004).
- Other: Primary and cleat hydraulic conductivity, soil type and thickness, other hydrologic pathways (i.e., abandoned coal mine, fractures, etc.).

Active coal fires are not traditional contaminant plumes; emissions are constantly escaping, not only through vents, but also through soil. The aforementioned measurements may yield important data, but caution should be exercised with regard to the interpretation of these data, especially in soil, because of the dynamic nature of coal-fire emissions. For example, for traditional contaminant-plume interpretation, the following may be used: (1) O_2 concentration for the effectiveness of microbial oxygen replenishment, (2) CO_2 as an indicator of aerobic respiration, and (3) CH_4 production as an indicator of anaerobic metabolism. In coal fires, however, these constituents are an intrinsic part of coal combustion, so they may or may not yield valuable information about attenuation. Coal fires are transient, changing location with time.

Total organic carbon may affect soil PAH levels at coal fires (Means et al., 1980; Weissenfels et al., 1992). Differing PAH degradation rates were observed when two industrial sites with different soil types were compared (Weissenfels et al., 1992). Sorption of organic pollutants onto soil organic matter significantly reduces biodegradability because sites within the soil matrix are less accessible. Such sorbed PAHs are probably not bioavailable and, thus, not biodegradable. This could be a factor

when comparing PAH levels at Truman Shepherd (heterogeneous soils caused by excavation) and Lotts Creek (organic forest soils).

3.4 Study Area Setting

3.4.1 Monitoring Sites - Truman Shepherd

The Truman Shepherd coal fire (Figure 14) is located within the Pennsylvanian Upper Elkhorn zone, Pikeville Formation, Breathitt Group, in the Appalachian Basin of eastern Kentucky (Figure 15). The site is in Knott County (latitude 37° 28' 18' N, longitude 82° 51' 07" W).

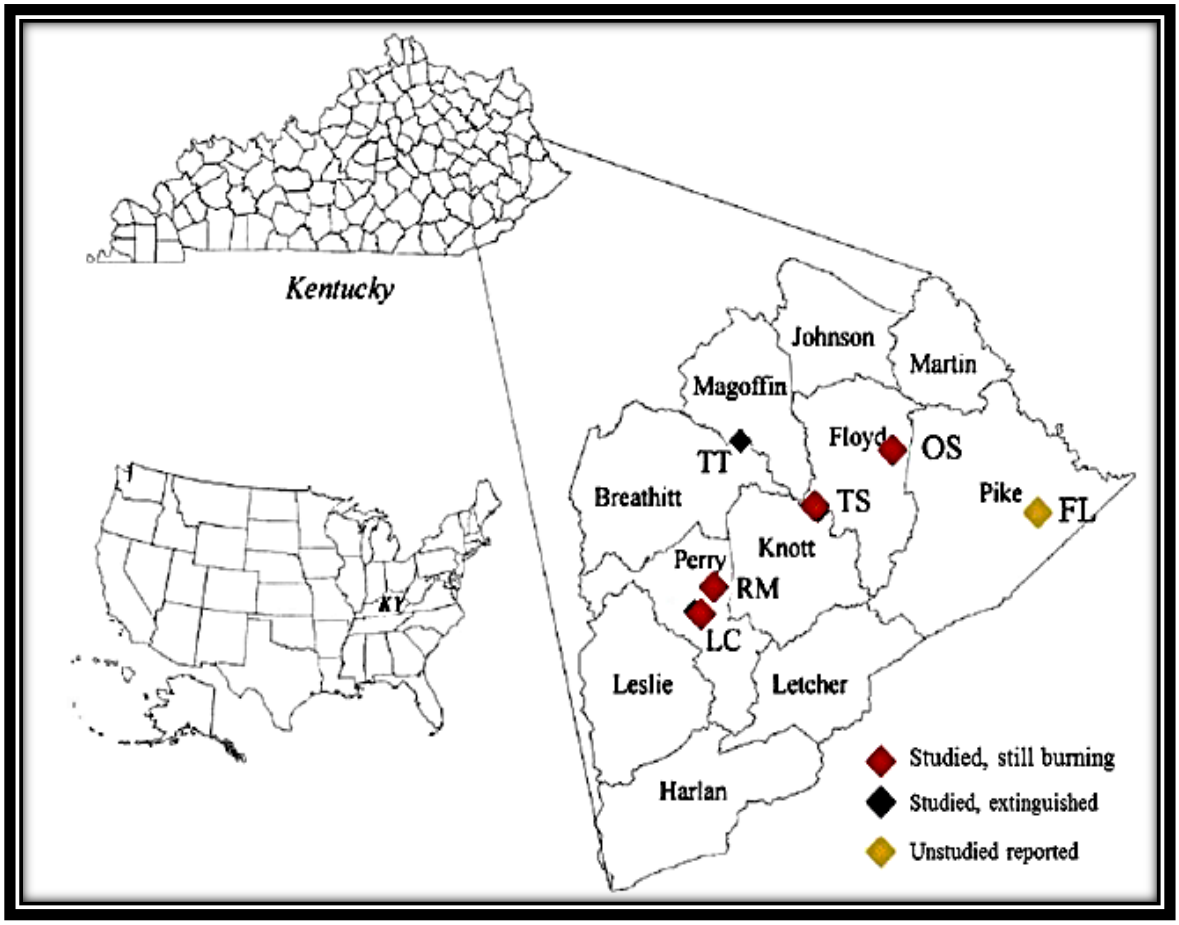

Figure 14: Coal-fire locations in eastern Kentucky studied by Hower et al. (2013). Truman Shepherd is indicated by TS and Lotts Creek is indicated by LC.

System	Group	Formation	Members and Beds	
Middle Pennsylvanian	**Breathitt**	**Princess**	Flint Ridge Flint	
			Richardson, Skyline coal	
			Broas coal	Hazard 10 coal
				Stoney Fork Member
		Four Corners		**Hindman, Hazard 9 coal**
			Peach Orchard coal	Hazard 8 coal
				Hazard 7 coal
				Hazard 5A
			Haddix coal	
			Magoffin Member	
		Hyden	Copeland, Taylor coal	
			Hamlin coal	
			Fire Clay rider	
			Fire Clay, Hazard 4	Fire Clay, Hazard 4
			Whitesburg coal	
			Kendrick Member	
		Pikeville	Amburgy coal	
			Elkins Fork Member	
			Upper Elkhorn 3 coal	
			Upper Elkhorn 2 coal	
			Upper Elkhorn 1 coal	
			Lower Elkhorn coal	
			Betsie Shale Member	

Figure 15: General stratigraphic section of the Eastern Kentucky Coal Field. Coals with fires studied in this report are in bold.

The coal fire is located in a valley bottom approximately 10 meters from the perennial Rock Fork Creek, approximately 50 meters upstream from its intersection with Howard Branch. The major soil group in the Truman Shepherd area (U.S. Department of Agriculture, 2004) is the Handshoe-Fedscreek-Marrowbone complex (Appendix IV), which consists of well-drained soils formed primarily from underlying siltstones, shales, and sandstones. Closely spaced, steep-sloped ridges separated by narrow valleys are

characteristic of the area. The soil cover is generally thin on the steep slopes common to the area, with the thickest accumulations in the valley bottoms and floodplains (Quinones et al., 1981).

Hydrogeologic connectivity between the Truman Shepherd fire and the neighboring Howard water well, 300 meters away, was assessed during an attempt by the U.S. Office of Surface Mining to extinguish the fire. In 2009, a fire-smothering foam was injected into old mine adits, and the foam appeared within a week of application in the Howard well (Hawkins, 2009). Based on the location of the outcrop of the Upper Elkhorn No. 1 to No. 3 coals along Rock Fork Road (Figure 16), the slight dip of the strata, and the increase in elevation toward the Howard property, the well probably intersects the coal seam in the shallow subsurface.

The coal seam was not visible in the uncased portion of the wellbore, but most likely is located in the cased upper 10 meters of the hole. Hawkins (2009) concluded that groundwater traveling through primary porosity would likely not reach the well within a week. Instead, groundwater is likely traveling through preferential pathways created by preexisting fractures, fractures created by subsidence from the fire, the old mine itself, or a combination of these. After foam injection, the U.S. Office of Surface Mining attempted to excavate inward approximately 10 meters from the highwall. Because of the excavation, the soil cover above the fire is heterogeneous, with no distinct soil horizons.

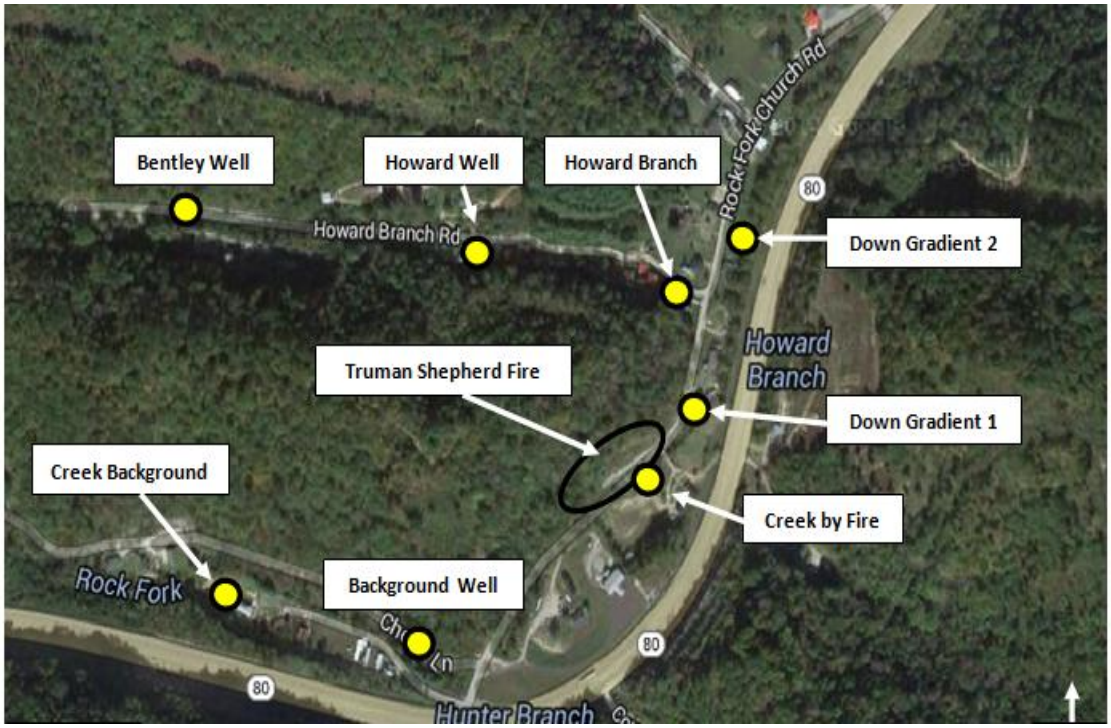

Figure 16. Truman Shepherd water sample locations. Distance from the Truman Shepherd fire to the Howard well is approximately 300 meters. White arrow indicates north. Excavation site is at latitude 37° 28' 18' N and longitude 82° 51' 07" W.

3.4.2 Lotts Creek

The Lotts Creek fire (Hower et al., 2012) is located in the Pennsylvanian Hindman (Hazard No. 9) coal bed, Four Corners Formation, Breathitt Group, in Perry County. The latitude is 37° 16' 19.3" N and longitude is 83° 08' 36.36" W. The Lotts Creek fire is located near a mountaintop in a forested area. The soil type is the Matewan-Marrowbone-Latham complex (Appendix IV); steep slopes, rocky terrain, and ridges are common. A thin organic soil layer is present, with sandy loam below originating from weathered sandstone parent material (U.S. Department of Agriculture, 1982). Neither groundwater nor surface water is abundant at this location because of the elevation (350 meters above sea level). The nearest stream, Left Fork of Upper Second Creek, is 280 meters to the south and has an elevation of 285 meters above sea level.

3.5 Regional Hydrogeology

Most groundwater in eastern Kentucky is obtained from shallow bedrock or alluvium wells, generally less than 30 meters deep (Wunsch, 1992). Sandstone aquifers are responsible for most water produced, but water may also be derived from other lithologies penetrated by the well, especially coal seams (Kiesler, 1986). Private residences in the area tend to be located in valley bottoms because of the greater availability of water and because of the relative ease of building on flat land compared to a steep slope (Wunsch, 1992). The largest water yields are usually derived from wells in valley bottoms and generally decrease upslope (Price et al., 1962).

Primary porosity in the Eastern Kentucky Coal Field is generally low. Price (1956) indicated that primary porosity ranges from 0.50 to 4.41 percent in the Breathitt Group. In contrast, primary porosity values in rocks of the Central Pennsylvania Coal Field may be more than twice as high (Brown and Parizek, 1971). Hawkins (2009) concluded that primary porosity in the Breathitt Group is "nonexistent" because of a high degree of cementation of sandstones, though the chemistry of cements was not discussed. The presence of fractures and joints, known as secondary porosity, creates additional openings that may store and transmit water, however. Freeze and Cherry (1979) suggested that secondary porosity values may be twice those of unfractured rocks.

Eastern Kentucky Coal Field rocks also exhibit low values of horizontal primary hydraulic conductivity. Values for sandstone and shale range from less than 0.018 centimeters/day to 42.13 centimeters/day, with an average of 3.75 centimeters/day. Secondary hydraulic conductivity values for near-surface, coal-field strata range from a minimum of 0.03 centimeters/day to 965.6 centimeters/day, with an average of 140.53 centimeters/day, however. Fracturing may increase hydraulic conductivity by several orders of magnitude (Schubert, 1980; Kipp and Dinger, 1987; Wright, 1987; Dixon and Rauch, 1988; Hasenfus et al., 1988; Harlow and LeCain, 1991; Hobba, 1991 Wunsch, 1992). Table 5 shows that horizontal primary hydraulic conductivity values for sandstone and shale are relatively low. Table 6 shows horizontal, field-measured hydraulic conductivities of coal-field strata that display secondary permeability from fractures.

Table 5: Horizontal primary hydraulic conductivity values for coal-field strata. After Minns (1993). PIT – Pressure-injection test; REC – Recovery test; PT – Pump test; ST – Slug test; CHIT – Constant head injection test.

Location	Lithology	K(cm/day)	Method	Reference
Eastern Kentucky	Sandstone	0.018–0.263	PIT	Kipp and Dinger (1987)
Eastern Kentucky	Shale	0.140–0.439	PIT	Kipp and Dinger (1987)
Eastern Kentucky	Sandstone	0.184	PIT	Wunsch (1992)
Eastern Kentucky	Shale	0.184	PIT	Wunsch (1992)
Southwest Virginia	Sandstone	0.176	PIT	Wright (1987)
Pennsylvania	>50% Sandstone	0.263–3.950	REC	Schubert (1980)
West Virginia	Sandstone	0.395	ST	Hasenfus (1988)
West Virginia	NA	0.614	PT	Hasenfus (1988)
West Virginia	Composite	42.135	CHIT	Dixon and Rauch (1988)
Southwest Virginia	Sandstone	0.034	PIT	Harlow and LeCain (1991)

Table 6: Horizontal secondary hydraulic conductivity values for fractured coal-field strata. After Minns (1993). PIT – Pressure-injection test; REC – Recovery test; PT – Pump test; ST – Slug test; CHIT – Constant head injection test.

Location	Lithology	K(cm/day)	Method	Reference
Eastern Kentucky	Sandstone	26.335	PIT	Wunsch (1992)
Southwest Virginia	Coal	8.778–79.004	PIT	Wunsch (1992)
Southwest Virginia	Fractures	6.145	PIT	Wright (1987)
West Virginia	Fractures	2.897	CHIT	Dixon and Rauch (1988)
West Virginia	Fractures	1.229–5.267	CHIT	Dixon and Rauch (1988)
Southwest Virginia	Various	0.030–7.461	PIT	Harlow and LeCain (1991)
West Virginia	Coal (max)	434.521–965.602	PT	Hobba (1991)
West Virginia	Coal (min)	61.447–228.233	PT	Hobba (1991)

Shales and underclays beneath coals act as aquitards to the vertical movement of water, which may result in horizontal flow through fractured/cleated coal seams (Wunsch, 1992). Coal seams can contain significant secondary porosity in the form of fractures or cleats (discussed below). Freeze and Cherry (1979) and Brown and Parizek (1971), in Pennsylvania studies, showed that horizontal flow in these types of aquifers is more prevalent than vertical flow. Schubert (1980) showed that vertical hydraulic conductivity is 10 to 50 times less than horizontal hydraulic conductivity in near-surface shales in Pennsylvania. Freeze and Cherry (1979) concluded that the ratio was 10 to 1. Schubert (1980) indicated that conductivities in near-surface sandstones are three times higher in the horizontal direction than in the vertical.

Abandoned mines can also act as pathways for horizontal water flow. Mining produces a network of large void spaces. These void spaces have orders of magnitude higher conductivity than surrounding rock layers (Kipp and Dinger, 1987). Subsidence above old mines can create fractures in overlying strata (Hawkins, 2009), which also influences groundwater movement in the coal field (Dinger et al., 1988).

3.6 Fracture Trends

Several types of fractures can influence surface bedrock in eastern Kentucky. Near-surface fractures are created by multiple mechanisms. Many shallow fractures, especially those on the outer margins of ridges, were formed by stress-relief forces, which are generated by rock mass removal from natural erosion processes (Hawkins, 2009). These stress-relief fractures tend to be vertical or near vertical along the hillsides, paralleling the main valleys; they become more common approaching valley bottoms (Wyrick and Borchers, 1981). The frequency and aperture of these fractures tend to decrease with increasing depth of cover (Hawkins et al., 1996). Fracturing created by stress-relief forces is commonly visible in roadcuts and other exposures.

Regional tectonic stresses can also create fractures that influence groundwater movement. These fractures tend to be more oblique (subvertical) than stress-relief fractures and generally extend to much greater depths (Hawkins et al., 1996). Photo lineament studies may indicate the existence of long, relatively narrow, heavily fractured zones that do not necessarily follow topography, and are inferred to be tectonic fractures.

These fractures substantially facilitate groundwater movement (Hawkins, 2009). In some cases, dominant and oblique subordinate (near rectangular) tectonic fracture trends can be delineated.

In coal beds, tectonic stresses result in the development of fractures called cleats. Coals generally contain two cleat orientations. The "face cleat" is predominant, and parallel to major structural trends, whereas the "butt cleat" is perpendicular to the face cleat (Minns, 1993). Hobba (1991) indicated that in West Virginia the direction of maximum transmissivity for both coal and overburden is nearly parallel to the face cleat, and transmissivity along the face cleat is three times greater than along the butt cleat. Hobba (1991) also showed that transmissivity in overburden in the minimum direction was 0.26 to 2.13 meters/day, whereas transmissivity in the maximum direction was 13.17 to 79 meters/day.

The Truman Shepherd fire is in an abandoned mine. Exactly when the mine was active is unknown, but local residents report that it was active in the 1930's and closed in the 1940's. According to John Hiett (Kentucky Division of Mine Safety, personal communication, 2014), there are no mine maps for the Truman Shepherd Mine. Shallow underground mines such as Truman Shepherd are susceptible to subsidence fractures from mining. Fractures can also be created or exacerbated by retreat mining, pillar removal, blasting, construction of haul roads, and other mining activities (Stephen Greb, Kentucky Geological Survey, personal communication, 2014). Which of these methods were used at this location is not known, however. In addition, thermal expansion and contraction are likely in the immediate vicinity of coal-mine fires as temperature changes. The repeated cycles lead to subsidence fractures. The processes mentioned in this section may significantly influence groundwater movement.

3.7 Methodology

In the vicinity of the Truman Shepherd fire, groundwater and surface-water samples were collected at the Howard well, the neighboring Bentley well, an adjoining stream, and other locations (Figure 16) during normal flow conditions. Because pre-fire samples were not available, an upstream sample and a background well sample were

collected as controls for surface water (see Figure 16). Nine soil samples were collected in the excavated area (Figure 17) and a background soil sample was collected 100 meters east of the fire.

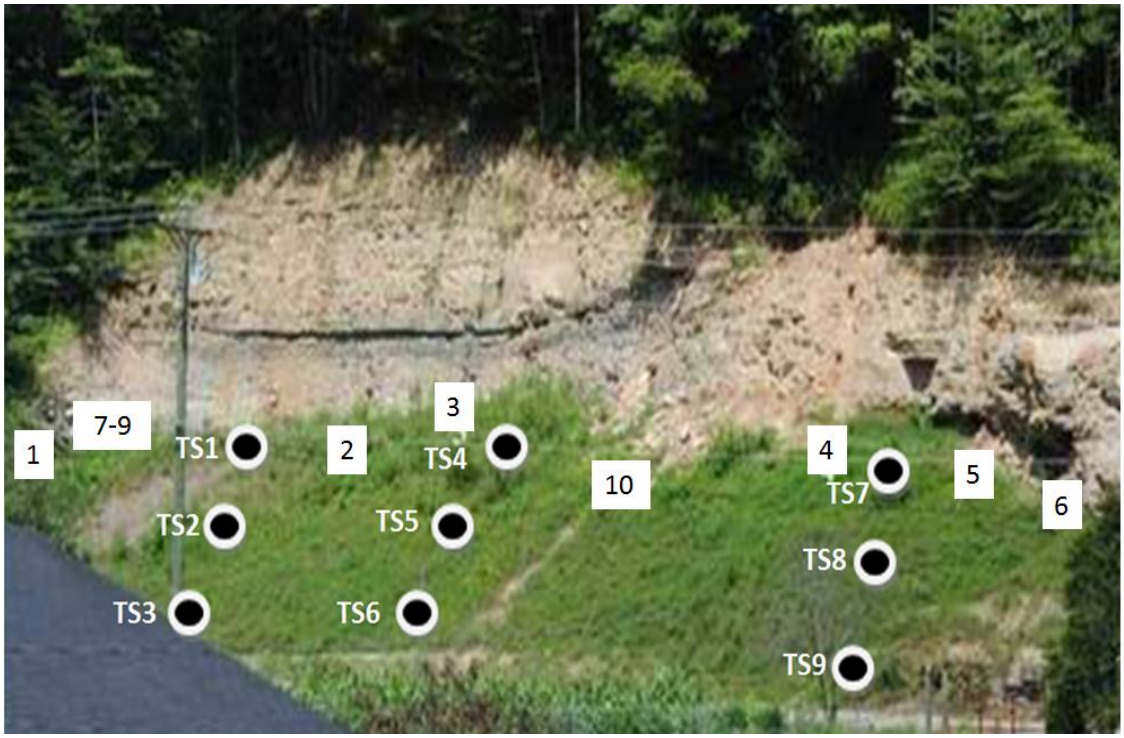

Figure 17: Locations of Truman Shepherd coal-fire vents (squares) and soil samples (black circles with a TS prefix).

In the vicinity of the Lotts Creek fire, the only place water was available was a ditch approximately 10 meters below the fire. Eighteen soil samples were collected at and around multiple coal-fire vents in spring, summer, and fall of 2014. The September sampling event was focused around vent 1 (Figure 18) at spacings of approximately 1 meter. Tars were discovered on the upper side of vent 1.

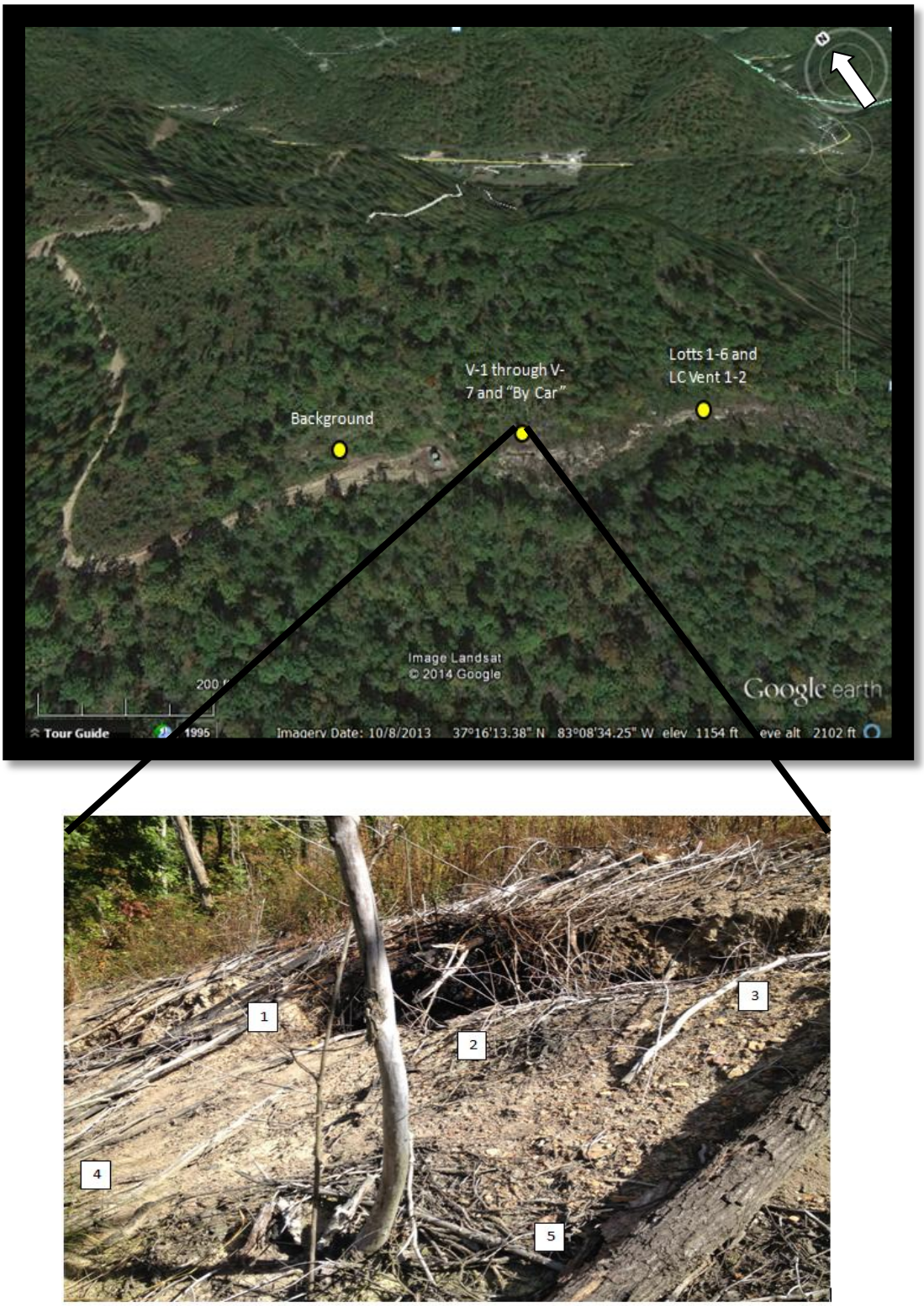

Figure 18: Google Earth and close-up views of Lotts Creek coal fire (latitude 37° 16' 19.3" N, longitude 83° 08' 36.36" W).Yellow circles represent sampling locations. Bottom image is a close-up of the V-1–V-7 and "By Car" sampling locations. V-6 (1 meter downhill of V-4) and V-7 (1 meter downhill of V-5) are not shown in the photograph.

Soil samples were collected in 59-milliliter glass jars for analysis of BTEX, PAHs, cyanide, and total organic carbon. For BTEX and PAH analyses, surface- and groundwater samples were collected in 40-milliliter amber glass VOA vials without headspace. Groundwater samples were collected from the Howard well, Bentley well, and background well (these domestic wells were not purged because it was impractical, and pH, EC, and T were not measured for the domestic well samples because of an instrumentation malfunction). EC, pH, T, and stream depth were measured for surface water ("grab" samples) (Appendix V). For cyanide analysis, water samples were collected in 100-milliliter glass bottles with NaOH to maintain a pH greater than 9. All soil and water samples were chilled for transport and storage. BTEX samples were shipped overnight to Remediation Products Inc. (Golden, Colorado) and analyzed by EPA method 8260B (Environmental Protection Agency, 1996a). PAH samples were shipped overnight to ESC Lab Sciences (Mount Juliet, Tennessee) and analyzed by EPA method 8270C (Environmental Protection Agency, 1996b). Cyanide samples were analyzed by EPA method SW-846 9012B (Environmental Protection Agency, 2004) at Microbac Laboratories in Lexington, Kentucky. Soil samples were analyzed for TOC at the University of Kentucky Center for Applied Energy Research by taking total organic carbon as the difference between total carbon and inorganic carbon (Gerald Thomas, Center for Applied Energy Research, personal communication, 2015). Safety precautions were taken by wearing a NIOSH-approved M Multi Gas/Vapor Cartridge/Filter 60926 P100 fitted mask to prevent inhaling potentially harmful emissions.

3.8. Results and Discussion

Except for one detection of ethylbenzene at 0.00064 milligrams/liter in Howard Branch, the Truman Shepherd coal mine fire yielded no detectable BTEX, PAHs, or cyanide in water samples (Table 7 and Table 8).

Table 7. BTEX and cyanide concentrations in water samples from Truman Shepherd. Asterisk indicates a compound considered carcinogenic. All units are in milligrams/liter, except AMU (atomic mass in g). MCL is EPA maximum contaminant level for tap water, DL is detection limit and BDL is below detection limit. Cells in gray highlight detectable concentrations below MCL.

Constituent →	Benzene (C_6H_6)*	Toluene (C_7H_8)	Ethylbenzene (C_8H_{10})	Xylene (C_8H_{10})	Cyanide
AMU→	78	92	106	106	26
MCL →	0.0005	1.1	0.0015	0.19	0.2
DL →	0.0005	0.0005	0.0005	0.0005	0.010
Howard well	BDL	BDL	BDL	BDL	BDL
Bentley well	BDL	BDL	BDL	BDL	BDL
(Rock) Creek	BDL	BDL	BDL	BDL	BDL
Background Creek	BDL	BDL	BDL	BDL	BDL
Background well	BDL	BDL	BDL	BDL	BDL
Creek 1 at Fire	BDL	BDL	BDL	BDL	BDL
Downgradient well	BDL	BDL	BDL	BDL	BDL
Howard Branch	BDL	BDL	0.00064	BDL	BDL
Blank	BDL	BDL	BDL	BDL	BDL

Table 8. PAH concentrations in water samples from Truman Shepherd. Asterisk indicates a compound considered carcinogenic. All units are in milligrams/liter, except AMU (atomic mass in g). MCL is EPA maximum contaminant level for tap water. DL is detection limit and BDL is below detection limit.

Constituent	Naphthalene ($C_{10}H_8$)*	Acenaphthylene ($C_{12}H_8$)	Acenaphthene ($C_{12}H_{10}$)	Fluorene ($C_{13}H_{10}$)	Anthracene ($C_{14}H_{10}$)	Phenanthrene ($C_{14}H_{10}$)	Pyrene ($C_{16}H_{10}$)	Fluoranthene ($C_{16}H_{10}$)
AMU→	128	152	154	166	178	178	202	202
MCL→	0.00054	NA	0.53	0.29	1.8	NA	0.12	0.8
DL →	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Howard well	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bentley well	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Creek	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Background Creek	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Background well	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Well 1 at Fire	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Downgradient well	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Howard Branch	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Blank	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

Table 8 continued:

Constituent	Chrysene ($C_{18}H_{12}$)	Benzo(a)anthracene ($C_{18}H_{12}$)*	Benzo(k)fluoranthene ($C_{20}H_{12}$)*	Benzo(a)pyrene ($C_{20}H_{12}$)*	Benzo(b)fluoranthene ($C_{20}H_{12}$)*	Indeno(1,2,3-cd)pyrene ($C_{22}H_{12}$)*	Benzo(g,h,i)perylene ($C_{22}H_{12}$)	Dibenz(a,h)anthracene ($C_{22}H_{14}$)*
AMU→	228	228	252	252	252	276	276	278
MCL→	0.0034	0.00001	0.00034	0.000003	0.000034	0.000034	NA	0.000003
DL →	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Howard well	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Bentley well	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Creek	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Background creek	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Background well	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Well 1 at Fire	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Downgradient well	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Howard Branch	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Blank	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

BTEX compounds detected in soil included xylene isomers in six of nine samples (TS1 to TS6; range 0.0005 to 0.002 milligrams/kilogram) (Table 9). The PAHs naphthalene and phenanthrene were detected in soil samples TS1 through TS7. Naphthalene concentrations ranged from 0.059 to 0.65 milligrams/kilogram (which exceed the EPA soil screening level of 0.000543 milligrams/kilogram) and phenanthrene concentrations ranged from 0.001 to 0.24 milligrams/kilogram (Table 10). Total organic carbon concentrations in samples TS1, TS2, and TS3 ranged from 3.18 to 4.06 percent carbon (Table 11); cyanide concentrations in the same samples were below the detection limit of 0.23–0.24 milligrams/kilogram.

Table 9. BTEX concentrations in soil samples from Truman Shepherd. Asterisk indicates a compound considered carcinogenic. All units are in milligrams/kilogram except AMU (atomic mass in grams). SSLs are 2015 risk-based soil screening levels implemented by the EPA. DL is detection limit and BDL is below detection limit. Cells in gray highlight detectable concentrations below the SSL. For benzene, the SSL may be lower than the DL.

Constituent	Benzene (C_6H_6)*	Toluene (C_7H_8)	Ethylbenzene (C_8H_{10})	Xylene (C_8H_{10})
AMU→	78	92	106	106
SSLs→	0.000233	0.762	0.00167	0.19
DL →	0.0005	0.0005	0.0005	0.0005
TS1	BDL	BDL	BDL	0.001
TS2	BDL	BDL	BDL	0.00081
TS3	BDL	BDL	BDL	0.0005
TS4	BDL	BDL	BDL	0.00098
TS5	BDL	BDL	BDL	0.002
TS6	BDL	BDL	BDL	0.00084
TS7	BDL	BDL	BDL	BDL
TS8	BDL	BDL	BDL	BDL
TS9	BDL	BDL	BDL	BDL

Table 10. PAH concentrations in soil samples from Truman Shepherd. Asterisk indicates compounds considered carcinogenic. All units are in milligrams/kilogram except AMU (atomic mass in grams). SSLs are the 2015 risk-based soil screening levels implemented by the EPA. DL is detection limit and BDL is below detection limit. Cells in gray highlight detectable concentrations below SSLs. Cells in magenta indicate concentrations above EPA SSLs.

Constituent	Naphthalene ($C_{10}H_8$)*	Acenaphthylene ($C_{12}H_8$)	Acenaphthene ($C_{12}H_{10}$)	Fluorene ($C_{13}H_{10}$)	Anthracene ($C_{14}H_{10}$)	Phenanthrene ($C_{14}H_{10}$)	Pyrene ($C_{16}H_{10}$)	Fluoranthene ($C_{16}H_{10}$)
AMU	128	152	154	166	178	178	202	202
SSLs	0.000543	NA	5.5	5.4	58	NA	13	89
DL	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
TS1	**0.1**	BDL	BDL	BDL	BDL	0.14	BDL	BDL
TS2	**0.22**	BDL	BDL	BDL	BDL	0.15	BDL	BDL
TS3	**0.078**	BDL	BDL	BDL	BDL	0.073	BDL	BDL
TS4	**0.059**	BDL	BDL	BDL	BDL	0.043	BDL	BDL
TS5	**0.086**	BDL	BDL	BDL	BDL	0.061	BDL	BDL
TS6	**0.65**	BDL	BDL	BDL	BDL	0.24	BDL	BDL
TS7	**0.09**	BDL	BDL	BDL	BDL	0.001	BDL	BDL
TS8	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TS9	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

Table 10 continued:

Constituent	Chrysene ($C_{18}H_{12}$)	Benzo(a)anthracene ($C_{18}H_{12}$)*	Benzo(k)fluoranthene ($C_{20}H_{12}$)*	Benzo(a)pyrene ($C_{20}H_{12}$)*	Benzo(b)fluoranthene ($C_{20}H_{12}$)*	Indeno(1,2,3-cd)pyrene ($C_{22}H_{12}$)*	Benzo(g,h,i)perylene ($C_{22}H_{12}$)	Dibenz(a,h)anthracene ($C_{22}H_{14}$)*
AMU	228	228	252	252	252	276	276	278
SSLs	1.2	0.00425	0.4	0.004	0.041	0.13	NA	0.013
DL	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
TS1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TS2	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TS3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TS4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TS5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TS6	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TS7	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TS8	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TS9	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

Table 11. TOC concentrations in soil samples from Truman Shepherd (TS1–TS3) and Lotts Creek (V1–V7 and BG) in percent carbon. Refer to Figure 17 and Figure 18 for sample locations.

Sample Location	TOC
TS1	4.06
TS2	3.47
TS3	3.18
V1	6.39
V2	14.32
V3	6.32
V4	8.43
V5	7.25
V6	12.78
V7	6.02
BG	2.98

No water contamination was observed at Lotts Creek. In contrast to the Truman Shepherd site, however, each BTEX compound was found in multiple soil samples, some of which were above EPA soil screening levels (Table 12). No BTEX compounds were detected in samples Lotts-1 through Lotts-6, LC Vent 1, or LC 2A, but all BTEX compounds were found in the background soil sample (BG), perhaps indicating atmospheric transport of volatile contaminants. Soil screening levels of xylene (0.038 milligram/kilogram, at site LC By Car) were an order of magnitude greater than at Truman Shepherd. In addition, each PAH compound analyzed was detected in at least one soil sample, and all samples except BG contained multiple detectable PAHs (Table 13). All PAH compounds were detected at site LC By Car, with concentrations of all compounds heavier than phenanthrene exceeding the SSL; the soil screening level concentration of benzo(a)anthracene (32 milligrams/kilogram) exceeded the soil screening level by a factor of over 7,000. All compounds heavier than phenanthrene also exceeded soil screening levels at site V2, with the concentration of pyrene (64 milligrams/kilogram) being the highest of any PAH analyzed at Lotts Creek. Most PAHs heavier than phenanthrene exceeded soil screening levels at sites V1 and V6 as well. Total organic carbon concentrations at sites V1 to V7 (6.02 to 14.32 milligrams/kilogram) were greater than background at Lotts Creek (2.98 milligrams/kilogram) and all total organic carbon values at Truman Shepherd (Table 11). Cyanide concentrations were detectable in all soil samples analyzed for total organic carbon except for V5 and the background sample. Detected cyanide concentrations exceeded the soil screening level and ranged from 0.38 to 0.66 milligrams/kilogram (Table 14).

Table 12. BTEX concentrations in soil samples from Lotts Creek. All units are in milligrams/kilogram, except AMU (atomic mass in grams). Asterisk indicates compounds considered carcinogenic. All units are in milligrams/kilogram except AMU (atomic mass in grams). SSLs are the 2015 risk-based soil screening levels implemented by the EPA. DL is detection limit and BDL is below detection limit. Cells in gray highlight detectable concentrations below soil screening levels. Cells in magenta indicate concentrations above soil screening levels. For benzene, the soil screening level may be lower than the DL.

Constituent	Benzene (C_6H_6)*	Toluene (C_7H_8)	Ethylbenzene (C_8H_{10})	Xylene (C_8H_{10})
AMU →	78	92	106	106
SSLs→	0.000233	0.762	0.00167	0.19
DL →	0.0005	0.0005	0.0005	0.0005
Lotts-1	BDL	BDL	BDL	BDL
Lotts-2	BDL	BDL	BDL	BDL
Lotts-3	BDL	BDL	BDL	BDL
Lotts-4	BDL	BDL	BDL	BDL
Lotts-5	BDL	BDL	BDL	BDL
Lotts-6	BDL	BDL	BDL	BDL
LC Vent 1	BDL	BDL	BDL	BDL
LC Vent 2	**0.00052**	0.00052	BDL	BDL
LC 2A	BDL	BDL	BDL	BDL
LC By Car	**0.0005**	0.00072	**0.00192**	0.038
V1	**0.001**	0.004	**0.0045**	0.02637
V2	BDL	0.003	0.001	0.00317
V3	**0.00061**	0.002	0.0003	0.001
V4	BDL	0.001	BDL	0.0006
V5	**0.0001**	0.005	BDL	0.00129
V6	**0.000158**	0.007	0.001	0.00199
V7	BDL	0.00156	0.001	0.00168
BG	**0.0011**	0.0044	0.00074	**0.7524**

Table 13. PAH concentrations in soil samples from Lotts Creek. Asterisk indicates compounds considered carcinogenic. All units are in milligrams/kilogram except AMU (atomic mass in grams). SSLs are 2015 risk-based soil screening levels implemented by the EPA. DL is detection limit and BDL is below detection limit. Cells in gray highlight detectable concentrations below soil screening levels. Cells in magenta indicate concentrations above EPA soil screening levels.

Constituent	Naphthalene ($C_{10}H_8$)*	Acenaphthylene ($C_{12}H_8$)	Acenaphthene ($C_{12}H_{10}$)	Fluorene ($C_{13}H_{10}$)	Anthracene ($C_{14}H_{10}$)	Phenanthrene ($C_{14}H_{10}$)	Pyrene ($C_{16}H_{10}$)	Fluoranthene ($C_{16}H_{10}$)
AMU	128	152	154	166	178	178	202	202
SSLs	0.000543	NA	5.5	5.4	58	NA	13	89
DL	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Lotts-1	**0.37**	BDL	BDL	BDL	0.25	2.8	1.3	2.1
Lotts-2	**0.16**	BDL	BDL	BDL	BDL	0.21	0.11	0.15
Lotts-3	**0.12**	BDL	BDL	BDL	0.036	0.21	0.14	0.18
Lotts-4	**0.095**	BDL	BDL	BDL	BDL	0.16	0.13	0.17
Lotts-5	BDL	BDL	BDL	BDL	BDL	BDL	0.035	BDL
Lotts-6	BDL	BDL	BDL	BDL	BDL	0.04	0.055	0.057
LC Vent 1	**0.048**	BDL	BDL	0.012	0.11	0.67	0.6	0.76
LC Vent 2	**0.021**	BDL	BDL	BDL	0.021	0.074	0.41	0.36
LC 2A	**0.052**	BDL	BDL	BDL	BDL	0.016	0.048	0.02
LC By Car	**0.35**	0.12	0.11	0.75	5.4	7.7	**38**	29
V1	0.7	BDL	BDL	1.1	4.9	15	**32**	21
V2	BDL	1.9	BDL	BDL	5.2	4.7	**64**	24
V3	BDL	BDL	BDL	BDL	0.26	0.42	0.84	0.54
V4	BDL	BDL	BDL	BDL	0.29	0.52	1.4	0.55
V5	**0.045**	BDL	BDL	BDL	0.061	0.082	0.23	0.12
V6	BDL	BDL	BDL	BDL	0.66	0.59	9.1	1.1
V7	BDL	BDL	BDL	BDL	0.19	BDL	1.6	BDL
BG	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

Table 13 continued:

Constituent	Chrysene ($C_{18}H_{12}$)	Benzo(a)anthracene ($C_{18}H_{12}$)*	Benzo(k)fluoranthene ($C_{20}H_{12}$)*	Benzo(a)pyrene ($C_{20}H_{12}$)*	Benzo(b)fluoranthene ($C_{20}H_{12}$)*	Indeno(1,2,3-cd)pyrene ($C_{22}H_{12}$)*	Benzo(g,h,i)perylene ($C_{22}H_{12}$)	Dibenz(a,h)anthracene ($C_{22}H_{14}$)*
AMU	228	228	252	252	252	276	276	278
SSLs	1.2	0.00425	0.4	0.004	0.041	0.13	NA	0.013
DL	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Lotts-1	**3.2**	**1.2**	**0.74**	**0.9**	**4**	**0.91**	1.1	**0.36**
Lotts-2	0.086	BDL	BDL	BDL	**0.063**	BDL	BDL	BDL
Lotts-3	0.11	**0.045**	BDL	**0.034**	**0.095**	BDL	0.037	BDL
Lotts-4	0.2	**0.071**	0.044	**0.08**	**0.22**	0.064	0.084	BDL
Lotts-5	0.04	BDL	BDL	**0.039**	**0.084**	0.034	0.04	BDL
Lotts-6	0.036	BDL	BDL	BDL	0.036	BDL	BDL	BDL
LC Vent 1	1	**0.38**	0.22	**0.26**	**1.2**	**0.26**	0.3	0.1
LC Vent 2	0.3	**0.17**	0.022	**0.03**	**0.11**	0.036	0.038	0.013
LC 2A	0.056	**0.036**	0.028	**0.08**	**0.14**	0.066	0.073	**0.024**
LC By Car	**41**	**32**	**7.9**	**11**	**31**	**3.7**	4.6	**2**
V1	**15**	**11**	**0.81**	**1.7**	**5**	**0.52**	0.8	BDL
V2	**17**	**16**	**5.4**	**13**	**22**	**5.9**	8.4	**2.6**
V3	**1.4**	**0.46**	**0.45**	**1.3**	**2.5**	**0.98**	1.4	**0.47**
V4	**1.5**	**0.51**	0.3	**0.77**	**2**	**0.73**	1	**0.31**
V5	0.27	BDL	BDL	BDL	**0.34**	BDL	0.22	BDL
V6	**3.2**	**0.74**	**1.6**	**4.8**	**7.5**	**2.2**	3	**1.1**
V7	0.92	BDL	**0.44**	**0.74**	**1.8**	**0.66**	0.98	**0.27**
BG	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL

Table 14. Cyanide concentrations in soil samples from Lotts Creek in milligrams/kilogram. EPA soil screening level for cyanide is 0.00148 milligrams/kilogram. DL is 0.25 milligrams/kilogram. See Figure 5 for sample locations.

Sample Location	Cyanide
V1	**0.38**
V2	**0.45**
V3	**0.36**
V4	**0.43**
V5	BDL
V6	**0.66**
V7	**0.52**
BG	BDL

3.9. Conclusions

At both the Truman Shepherd and Lotts Creek sites, BTEX and PAH compounds were essentially undetectable in water samples (one compound was detected in one sample). BTEX and PAHs were more prevalent in soil samples at Lotts Creek than at Truman Shepherd. Concentrations of PAHs tended to be greater than concentrations of BTEX at both sites, and concentrations of mid- to high-mass PAHs exceeded soil screening levels in multiple soil samples at Lotts Creek. But contamination levels decreased precipitously away from the vents.

The tendency for concentrations of BTEX and PAH compounds to be greater in soil than in water, and the greater concentrations of PAHs relative to BTEX, can be explained by preferential partitioning (sorption) to soil organic matter, which increases with atomic mass and the complexity of molecular structure (Fetter, 1999). Similarly, the greater BTEX and PAH concentrations in soils at Lotts Creek could reflect increased sorption capacity associated with greater total organic carbon values (Fetter, 1999). Other physicochemical mechanisms, including dilution, volatilization, and biodegradation, may attenuate contaminant concentrations near mine fires (Fetter, 1999). Thermophilic bacterial activity has been identified at another mine-fire site in eastern Kentucky (Wang et al., 2014), but that was beyond the scope of this study.

Overall, there are both similarities and differences between contamination observed at underground coal gasification sites and at the Truman Shepherd and Lotts Creek fires. Contamination from underground coal gasification sites were used as proxies because there are no known groundwater studies for coal fires. Similarities include the tendency for organic compounds and cyanide to decrease to background levels within a few meters of the site of combustion. Differences include a lack of detectable contaminants in groundwater and surface water at the coal-fire sites. This may result from differences in soils and geologic settings. Most of the relevant underground coal gasification sites profiled were located in low-relief terrains in Texas and Wyoming, rather than the steep hills of eastern Kentucky. Some underground coal gasification sites included numerous closely spaced monitoring wells near the burn cavity. Installation of

such wells, which might have identified contaminants in groundwater, was not feasible in this study. Because groundwater could not be sampled directly, I had to rely on the closest well, which was more than 300 meters from the Truman Shepherd fire. Fractures or changes in the coal-mine could also influence groundwater flow. A comparison of underground coal gasification and coal fires conclusions is outlined below:

Underground Coal Gasification Conclusions	**Coal Fire Conclusions**	**Agreement?**
Computer models indicate that groundwater velocity is the most important variable in chemical migration in underground coal gasification.	Groundwater contamination was not found, but primary hydraulic conductivities are very low at the study sites, unless traveling through fractures or mine shafts, in which case dilution would be a factor.	NA/General Agreement
The quality of information in underground coal gasification tests is an important factor to consider.	There is no reason to believe that results from this study were inaccurate. Samples were collected at two fires with similar geologies, and were analyzed by the same EPA-approved methods at the same laboratories.	Agree
High pressures and temperatures ward off water from the burn cavity but force volatile and semivolatile species out of the burn cavity and into the surrounding strata, causing significant groundwater-quality changes.	Although volatile and semivolatile species were found in soil samples (sometimes at high levels), groundwater contamination was not found.	Partial
TOC, BTEX, and naphthalene increase dramatically as much as 30 meters from the burn cavity.	TOC, BTEX, and PAHs were found above soil screening levels in soil at Lotts Creek. Naphthalene was also found above soil screening levels at Truman Shepherd. Soil contamination was found in the immediate vicinity of the coal fire vents, with concentrations decreasing precipitously away from the vents.	General Agreement
Hydrogen cyanide moves out of the burn cavity and yields high cyanide concentrations in surrounding strata.	Seven cyanide samples were collected at Lotts Creek. Concentrations were detectable in all soil samples except for V5 and the background sample. Detected cyanide concentrations exceeded the soil screening level (0.00148 milligram/kilogram) and ranged from 0.38 to 0.66 milligram/kilogram.	Agree
CO_2 and H_2, produced by pyrolysis of coal are forced out of the burn cavity as far as 30 meters into the surrounding strata.	CO_2 and CH_4 were detected in vent-gas samples (often in high concentrations), but soils and water were not sampled for these gases.	General Agreement

Most of the nonvolatile organic species in the groundwater appear to originate in a thin char ring around the burn cavity. Phenol concentrations in groundwater within this ring tend to be the highest found at underground coal gasification sites. Naphthalene is found principally in groundwaters within this ring, whereas benzene, toluene, and xylene typically reach their highest concentrations in these waters.	Because it was not physically or financially feasible to drill wells in the steep slopes of the coal fires, this hypothesis could not be tested. The hydrogeologically connected Howard well did not yield BTEX or PAH contamination, however.	NA/No
Two transport mechanisms dominate after underground coal gasification: convective mixing, which distributes species in a relatively small area around the burn cavity, and regional groundwater movement, which causes a plume of altered water quality downgradient.	Not tested.	NA
Concentrations for most species generated during underground coal gasification decrease rapidly with time and distance from the burn cavity.	Concentrations in soils decrease sharply away from coal fire vents.	General Agreement
Time and distance are by far the most important variables regarding contamination levels at underground coal gasification sites.	Although testing soil and water after coal fires are extinguished was not an option in this case, distance is an important factor with respect to contaminant reduction.	NA/General Agreement
Attenuation by dilution is much greater if flow occurs through fractures than through a homogeneous medium.	Flow at Truman Shepherd is likely through fractures or the mine itself. Dilution may explain the lack of groundwater contamination at detectable levels.	General Agreement

The extent of groundwater contamination in all of the underground coal gasification studies was contained within a 33-meter radius around the burn cavity, with most contained within a much narrower zone. In this zone, most constituents rapidly decrease in concentration because of sorption, dilution, biodegradation, and possibly other physicochemical processes.	The extent of groundwater contamination is not known at Truman Shepherd and Lotts Creek, but if there is contamination, it is likely restricted to an area similar to that in underground coal gasification. Sorption, dilution, biodegradation, and possibly other physicochemical processes are likely responsible for contaminant reduction.	General Agreement

4.0 Chapter 4 - Overall Conclusions and Recommendations for Future Studies

A number of items were considered in this work. Below is the list of hypotheses, objectives, and tasks formulated at the beginning of the dissertation, with results and conclusions:

Hypothesis	Objective	Tasks	Results and Conclusions
Scientists have used a variety of methods and technologies to quantify coal-fire data.	Review past works and list technologies used, noting qualitative and quantitative preference when applicable.	Review applicable literature and corroborate with experts in the field.	Eight years of coal-fire collection technologies were reviewed. A variety of methods and technologies were identified. Qualitative and quantitative preferences were noted.
Numerous uncontrolled variables affect the interpretation of coal-fire emissions.	Identify and list uncontrolled coal-fire variables.	Review applicable literature and corroborate with experts in the field.	Variables identified include complete/incomplete combustion; fire temperature and size; distance to fire; relative humidity and moisture in the system; geology, geochemistry, and age of coal; condition of the mine; sampling time of day; sampling equipment differences; and human error.
Geochemical relationships between certain coal-fire gases indicate that incomplete combustion is occurring.	Use PCA to determine which coal-fire gases have strong relationships.	Collect gases at five eastern Kentucky coal fires (78 data points), then analyze using PCA to identify patterns.	The strongest relationship was between CO and H_2S. T and CH_4 were also important. This indicates that incomplete combustion and PAH formation are likely occurring.
Truman Shepherd and Lotts Creek coal fires contribute to soil and water contamination. There are pollution discrepancies between these fires caused by landscape differences and excavation at Truman Shepherd.	Identify and define extent of soil and water contamination at Truman Shepherd and Lotts Creek.	Collect soil and water data around the Truman Shepherd and Lotts Creek fires.	No groundwater contamination was detected at either location. Soil contamination was found at both but was much higher at Lotts Creek, potentially because of sorption onto soil organic matter (which is lacking at Truman Shepherd because of excavation) and other physicochemical mechanisms. Soil contamination was localized to relatively small areas around coal-fire vents.

I examined technologies used in collecting coal-fire gases, relationships between gases from five Kentucky coal fires, and water and soil contamination from two eastern Kentucky coal fires. Hydrocarbon contamination was localized in this study, but there are thousands of coal fires worldwide. With political focus on greenhouse gases from anthropogenic sources, quantifying contributions from coal-seam and coal-mine fires makes sense as well. These sources are unregulated and, because of incomplete combustion, could produce greater concentrations of some harmful gases than coal-fired power plants. A consistent federal coal fire policy should be considered.

Although attempts by the U.S. Government at Truman Shepherd failed, attempts to mitigate coal fires are warranted. Could engineering a system designed to inject air into coal fires to engender more complete combustion (similar to underground coal gasification) be practical, thus reducing the amount of complex and harmful hydrocarbons? Groundwater and soil hydrocarbon contamination from underground coal gasification and coal fires is limited. CO_2 would still be produced, but CH_4 and other gases may be significantly reduced. In addition, complete combustion could generate electricity. Although the number of residents served would be limited by coal availability, among other factors, the energy produced could be harnessed in an environmentally friendly way so it is not wasted. These ideas may be impractical due to a number of factors; feasibility studies would need to be conducted to determine practicality.

Although this study provided insight regarding contamination at coal-fire sites, this is a first step in understanding the dynamics of coal-fire pollution. I recommend more research on coal fires in Kentucky and elsewhere.

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Appendix I - Gas vent data used in five Kentucky fires for PCA (color-coded per different locations and different dates).

Point	Location	Date	Vent	Flow Rate (m/s)	Temp. (°C)	Rel. Humid. (%)
1	Truman	7/14/2011	1	1.12	33.5	42.0
2	Truman	7/14/2011	2	1.02	54.0	66.2
3	Truman	7/14/2011	3	2.58	53.0	76.4
4	Truman	7/14/2011	4	0.48	46.2	85.4
5	Truman	7/14/2011	5	1.28	49.0	90.2
6	Truman	11/11/2011	1	1.80	12.9	35.6
7	Truman	11/11/2011	2	1.88	18.0	37.0
8	Truman	11/11/2011	3	1.70	15.5	55.7
9	Truman	11/11/2011	4	2.08	14.8	36.6
10	Truman	11/11/2011	5	1.38	19.0	90.2
11	Truman	11/11/2011	6	0.50	14.2	29.2
12	Truman	1/6/2012	1	0.64	15.9	19.8
13	Truman	1/6/2012	7	0.48	19.7	54.6
14	Truman	1/6/2012	8	0.46	26.0	77.8
15	Truman	1/6/2012	9	0.58	25.4	56.2
16	Truman	1/6/2012	2	1.14	33.9	24.4
17	Truman	1/6/2012	3	0.82	25.5	48.2
18	Truman	1/6/2012	10	0.34	27.9	20.8
19	Truman	1/6/2012	4	2.48	42.9	79.4
20	Truman	1/6/2012	5	0.31	24.1	39.0
21	Truman	1/6/2012	6	1.60	43.9	88.2
22	Tiptop	Nov-09	1	9.48	21.6	74.6
23	Tiptop	Nov-09	2	2.32	27.3	55.1
24	Tiptop	Nov-09	3	1.38	33.0	64.8
25	Tiptop	Nov-09	4	1.54	40.1	87.4
26	Tiptop	Nov-09	5	2.42	31.4	45.5
27	Tiptop	Nov-09	6	1.10	54.3	36.8
28	Tiptop	Nov-09	7	1.26	30.1	29.4
29	Tiptop	Nov-09	8	0.54	40.8	27.2
30	Tiptop	Nov-09	9	0.48	48.9	27.2
31	Tiptop	Nov-09	10	1.04	45.1	45.2
32	Old Smokey	May	1	1.22	28.1	56.8
33	Old Smokey	May	2	9.26	33.0	27.1
34	Old Smokey	May	3	2.07	30.8	25.3
35	Old Smokey	May	5	5.30	33.9	28.4
36	Old Smokey	May	6	2.88	36.4	39.9
37	Old Smokey	May	7	2.00	66.1	41.6

38	Old Smokey	May	8	0.98	53.4	29.0
39	Old Smokey	May	9	1.26	50.8	31.4
40	Old Smokey	May	10	1.44	49.7	33.2
41	Old Smokey	May	11	1.20	36.9	26.6
42	Old Smokey	May	12	0.70	32.7	27.2
43	Old Smokey	May	13	3.32	75.4	35.8
44	Old Smokey	May	14	1.68	58.1	43.8
45	Old Smokey	July	1	3.96	40.4	84.2
46	Old Smokey	July	2	0.66	27.7	65.6
47	Old Smokey	July	3	1.32	27.5	63.4
48	Old Smokey	July	5	1.14	27.5	68.6
49	Old Smokey	July	6	0.98	30.3	61.4
50	Old Smokey	July	7	1.38	58.2	73.6
51	Old Smokey	July	8	0.42	29.9	60.4
52	Old Smokey	July	13	1.28	40.9	67.2
53	Lotts Creek	2/24/2012	1	1.56	23.5	41.4
54	Lotts Creek	2/24/2012	2	0.98	24.8	41.6
55	Lotts Creek	2/24/2012	3	0.64	28.1	43.2
56	Lotts Creek	2/24/2012	4	0.84	19.6	41.2
57	Lotts Creek	2/24/2012	5	5.20	31.0	43.2
58	Lotts Creek	2/24/2012	6	0.60	21.9	42.5
59	Lotts Creek	2/24/2012	7	1.76	219.1	0.0
60	Lotts Creek	7/16/2012	1	2.36	42.0	51.4
61	Lotts Creek	7/16/2012	2	0.84	40.2	48.2
62	Lotts Creek	7/16/2012	3	0.62	105.5	79.0
63	Lotts Creek	7/16/2012	8	0.84	40.2	48.2
64	Lotts Creek	7/16/2012	10	1.98	78.8	33.6
65	Ruth Mullins	9/11/2009	3	1.00	24.1	88.0
66	Ruth Mullins	11/18/2009	1	2.30	38.9	29.8
67	Ruth Mullins	11/18/2009	2	0.62	16.8	62.6
68	Ruth Mullins	11/18/2009	3	1.90	56.6	40.1
69	Ruth Mullins	11/18/2009	4	0.84	34.0	79.5
70	Ruth Mullins	11/18/2009	5	3.72	96.5	25.2
71	Ruth Mullins	11/18/2009	6	0.38	16.4	93.4
72	Ruth Mullins	11/18/2009	7	0.28	18.0	65.6
73	Ruth Mullins	11/18/2009	8	2.78	18.7	69.2
74	Ruth Mullins	11/18/2009	9	0.96	18.1	67.2
75	Ruth Mullins	1/19/2010	1	2.00	10.9	69.8

Point	Location	Date	Vent	ρ (kg/m^3)	Baro. Pres. (kPa)	CO_2 flux (mg/s/m^2)
1	Truman	7/14/2011	1	1.11	98.81	1500
2	Truman	7/14/2011	2	1.00	98.76	30000
3	Truman	7/14/2011	3	1.00	98.76	53000
4	Truman	7/14/2011	4	1.04	98.78	6500
5	Truman	7/14/2011	5	1.02	98.80	25000
6	Truman	11/11/2011	1	1.21	99.52	740
7	Truman	11/11/2011	2	1.18	99.37	5800
8	Truman	11/11/2011	3	1.19	99.35	18000
9	Truman	11/11/2011	4	1.18	99.32	13000
10	Truman	11/11/2011	5	1.17	99.35	5100
11	Truman	11/11/2011	6	1.20	99.36	986
12	Truman	1/6/2012	1	1.19	98.65	11
13	Truman	1/6/2012	7	1.16	98.59	300
14	Truman	1/6/2012	8	1.13	98.58	900
15	Truman	1/6/2012	9	1.13	98.56	1111
16	Truman	1/6/2012	2	1.11	98.54	5111
17	Truman	1/6/2012	3	1.13	98.52	4221
18	Truman	1/6/2012	10	1.13	98.51	2444
19	Truman	1/6/2012	4	1.05	98.51	37500
20	Truman	1/6/2012	5	1.14	98.54	617
21	Truman	1/6/2012	6	1.05	98.55	17500
22	Tiptop	Nov-09	1	1.13	96.45	8900
23	Tiptop	Nov-09	2	1.11	96.48	330
24	Tiptop	Nov-09	3	1.08	96.58	1800
25	Tiptop	Nov-09	4	1.07	96.56	3000
26	Tiptop	Nov-09	5	1.09	96.60	730
27	Tiptop	Nov-09	6	1.02	96.55	770
28	Tiptop	Nov-09	7	1.10	96.55	530
29	Tiptop	Nov-09	8	1.06	96.50	630
30	Tiptop	Nov-09	9	1.03	96.53	1000
31	Tiptop	Nov-09	10	1.03	96.47	540
32	Old Smokey	May	1	1.08	96.33	9200
33	Old Smokey	May	2	1.09	96.33	57000
34	Old Smokey	May	3	1.10	96.33	270
35	Old Smokey	May	5	1.09	96.33	5200
36	Old Smokey	May	6	1.07	96.32	18000
37	Old Smokey	May	7	0.95	96.29	11000
38	Old Smokey	May	8	1.02	96.26	1800
39	Old Smokey	May	9	1.01	96.25	2600

40	Old Smokey	May	10	1.01	96.24	3100
41	Old Smokey	May	11	1.07	96.24	2700
42	Old Smokey	May	12	1.09	96.26	780
43	Old Smokey	May	13	0.91	96.27	18000
44	Old Smokey	May	14	0.98	96.29	10000
45	Old Smokey	July	1	1.04	96.76	85000
46	Old Smokey	July	2	1.10	96.77	3100
47	Old Smokey	July	3	1.11	96.76	110
48	Old Smokey	July	5	1.11	96.80	0
49	Old Smokey	July	6	1.10	96.80	1100
50	Old Smokey	July	7	0.95	96.78	8300
51	Old Smokey	July	8	1.11	96.76	850
52	Old Smokey	July	13	1.07	96.81	9600
53	Lotts Creek	2/24/2012	1	1.11	95.59	1100
54	Lotts Creek	2/24/2012	2	1.11	95.47	4600
55	Lotts Creek	2/24/2012	3	1.09	95.48	3900
56	Lotts Creek	2/24/2012	4	1.13	95.54	1000
57	Lotts Creek	2/24/2012	5	1.09	95.47	38000
58	Lotts Creek	2/24/2012	6	1.13	95.59	2600
59	Lotts Creek	2/24/2012	7	0.70	95.61	170000
60	Lotts Creek	7/16/2012	1	1.05	97.05	45000
61	Lotts Creek	7/16/2012	2	1.06	97.03	6000
62	Lotts Creek	7/16/2012	3	1.07	96.95	3000
63	Lotts Creek	7/16/2012	8	1.06	97.03	6000
64	Lotts Creek	7/16/2012	10	0.90	97.11	440000
65	Ruth Mullins	9/11/2009	3	1.13	97.43	1300
66	Ruth Mullins	11/18/2009	1	1.03	97.12	63000
67	Ruth Mullins	11/18/2009	2	1.15	97.14	760
68	Ruth Mullins	11/18/2009	3	1.02	97.13	120000
69	Ruth Mullins	11/18/2009	4	1.07	97.16	21000
70	Ruth Mullins	11/18/2009	5	0.89	97.16	610000
71	Ruth Mullins	11/18/2009	6	1.15	97.11	460
72	Ruth Mullins	11/18/2009	7	1.15	97.06	1200
73	Ruth Mullins	11/18/2009	8	1.14	96.92	7900
74	Ruth Mullins	11/18/2009	9	1.14	96.94	1400
75	Ruth Mullins	1/19/2010	1	5.36	98.12	12000

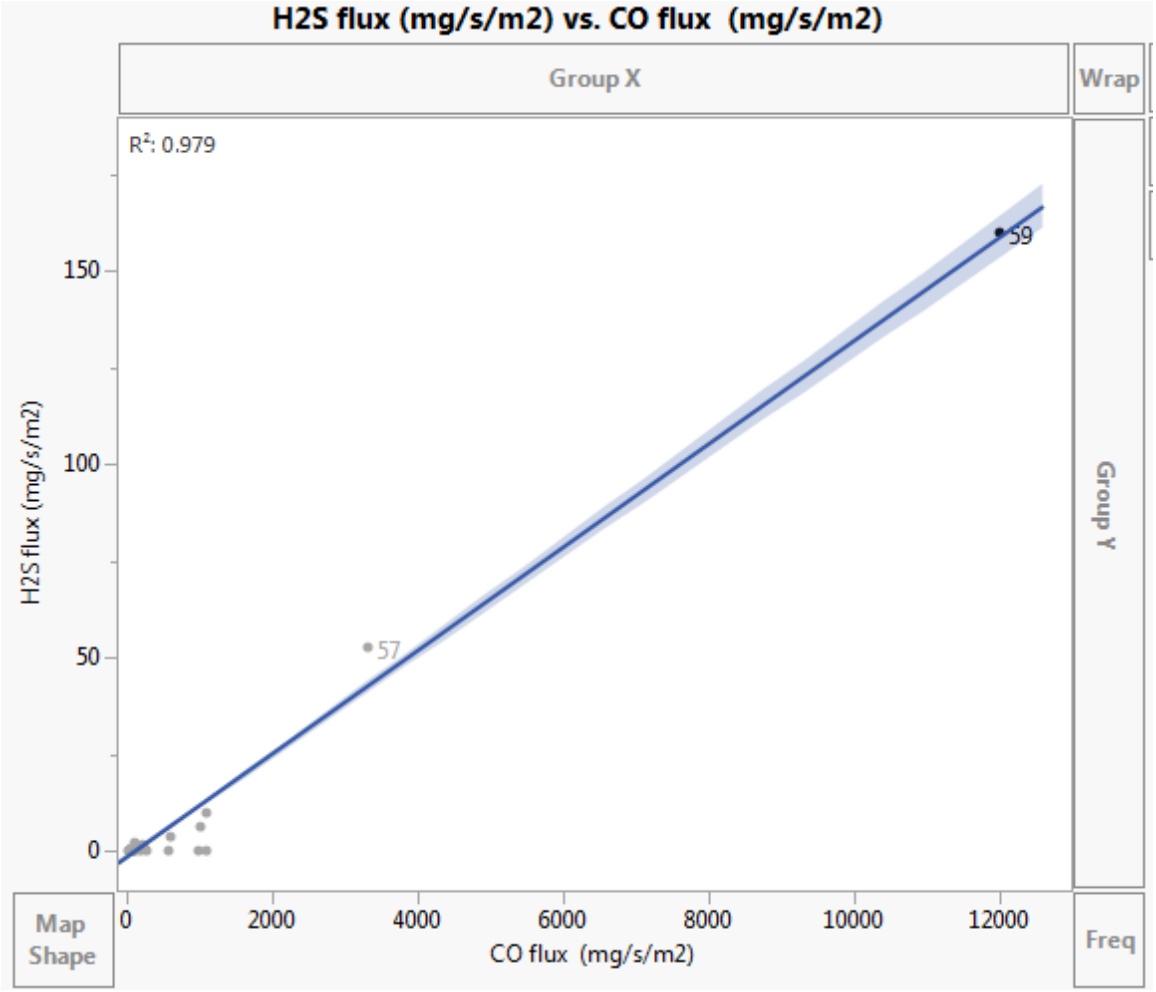
Point	Location	Date	Vent	CO flux ($mg/s/m^2$)	CH_4 flux ($mg/s/m^2$)	H_2S flux (mg/s/m2)
1	Truman	7/14/2011	1	13.0	0	0.01
2	Truman	7/14/2011	2	19.0	80	0.00
3	Truman	7/14/2011	3	19.0	130	0.00
4	Truman	7/14/2011	4	19.0	34	0.00
5	Truman	7/14/2011	5	47.0	120	0.00
6	Truman	11/11/2011	1	1.7	0	0.00
7	Truman	11/11/2011	2	2.7	1.7	0.00
8	Truman	11/11/2011	3	28.0	1300	0.01
9	Truman	11/11/2011	4	7.2	3.2	0.00
10	Truman	11/11/2011	5	21.0	6.8	0.01
11	Truman	11/11/2011	6	10.8	1.7	0.00
12	Truman	1/6/2012	1	0.2	0.0	0.00
13	Truman	1/6/2012	7	2.3	0.0	0.00
14	Truman	1/6/2012	8	6.1	0.2	0.00
15	Truman	1/6/2012	9	4.0	0.3	0.00
16	Truman	1/6/2012	2	3.1	0.4	0.00
17	Truman	1/6/2012	3	6.0	0.7	0.00
18	Truman	1/6/2012	10	5.3	0.2	0.00
19	Truman	1/6/2012	4	16.9	3.1	0.00
20	Truman	1/6/2012	5	6.1	0.2	0.00
21	Truman	1/6/2012	6	68.8	7.2	0.01
22	Tiptop	Nov-09	1	0.0	0	0.00
23	Tiptop	Nov-09	2	0.0	0	0.00
24	Tiptop	Nov-09	3	0.4	0	0.00
25	Tiptop	Nov-09	4	0.2	0	0.00
26	Tiptop	Nov-09	5	5.8	0	0.00
27	Tiptop	Nov-09	6	0.9	0	0.00
28	Tiptop	Nov-09	7	7.5	0	0.00
29	Tiptop	Nov-09	8	0.5	0	0.00
30	Tiptop	Nov-09	9	1.2	0	0.00
31	Tiptop	Nov-09	10	3.5	0	0.00
32	Old Smokey	May	1	41.0	78	0.01
33	Old Smokey	May	2	89.0	1400	0.25
34	Old Smokey	May	3	0.0	0	0.00
35	Old Smokey	May	5	21.0	0	0.04
36	Old Smokey	May	6	87.0	320	0.07
37	Old Smokey	May	7	33.0	190	0.01

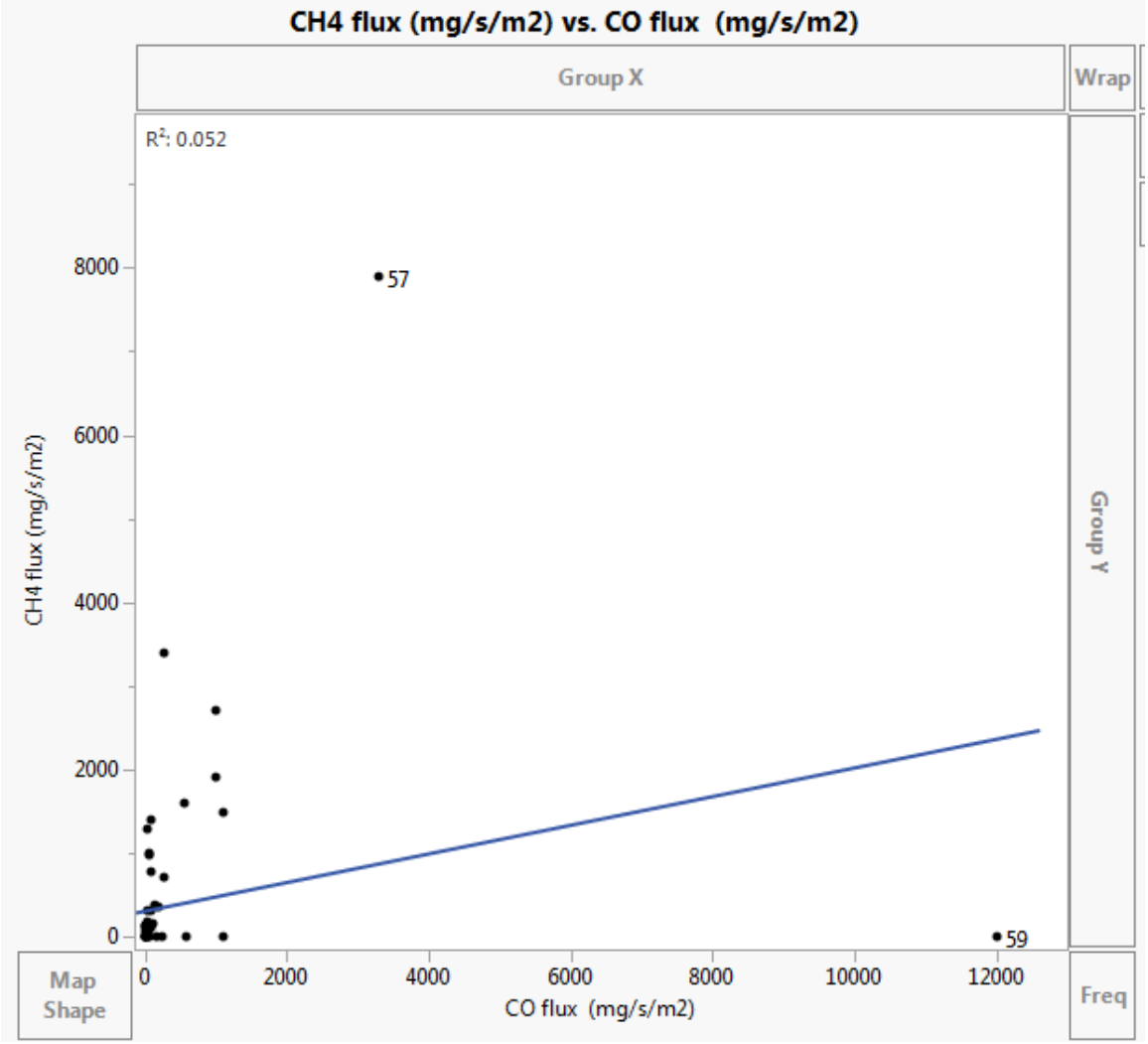
38	Old Smokey	May	8	7.2	11	0.00
39	Old Smokey	May	9	25.0	0	0.01
40	Old Smokey	May	10	3.5	0	0.00
41	Old Smokey	May	11	20.0	110	0.01
42	Old Smokey	May	12	13.0	0	0.00
43	Old Smokey	May	13	280.0	3400	0.09
44	Old Smokey	May	14	95.0	780	0.02
45	Old Smokey	July	1	43.0	320	0.02
46	Old Smokey	July	2	56.0	970	0.01
47	Old Smokey	July	3	0.0	0	0.00
48	Old Smokey	July	5	2.7	0	0.00
49	Old Smokey	July	6	9.9	0	0.00
50	Old Smokey	July	7	33.0	130	0.00
51	Old Smokey	July	8	4.8	0	0.00
52	Old Smokey	July	13	280.0	710	0.08
53	Lotts Creek	2/24/2012	1	98.0	120	2.40
54	Lotts Creek	2/24/2012	2	590.0	0	4.10
55	Lotts Creek	2/24/2012	3	200.0	350	1.70
56	Lotts Creek	2/24/2012	4	59.0	85	0.59
57	Lotts Creek	2/24/2012	5	3300.0	7900	53.00
58	Lotts Creek	2/24/2012	6	250.0	0	0.79
59	Lotts Creek	2/24/2012	7	12000.0	0	160.00
60	Lotts Creek	7/16/2012	1	1000.0	1900	6.70
61	Lotts Creek	7/16/2012	2	130.0	370	1.60
62	Lotts Creek	7/16/2012	3	71.0	1000	0.94
63	Lotts Creek	7/16/2012	8	130.0	370	1.60
64	Lotts Creek	7/16/2012	10	1100.0	0	10.00
65	Ruth Mullins	9/11/2009	3	2.1	0	0.02
66	Ruth Mullins	11/18/2009	1	570.0	1600	0.09
67	Ruth Mullins	11/18/2009	2	15.0	0	0.00
68	Ruth Mullins	11/18/2009	3	1100.0	1500	0.13
69	Ruth Mullins	11/18/2009	4	110.0	160	0.01
70	Ruth Mullins	11/18/2009	5	990.0	2700	0.16
71	Ruth Mullins	11/18/2009	6	180.0	0	0.02
72	Ruth Mullins	11/18/2009	7	25.0	0	0.00
73	Ruth Mullins	11/18/2009	8	50.0	0	0.00
74	Ruth Mullins	11/18/2009	9	23.0	0	0.00
75	Ruth Mullins	1/19/2010	1	130.0	260	0.05

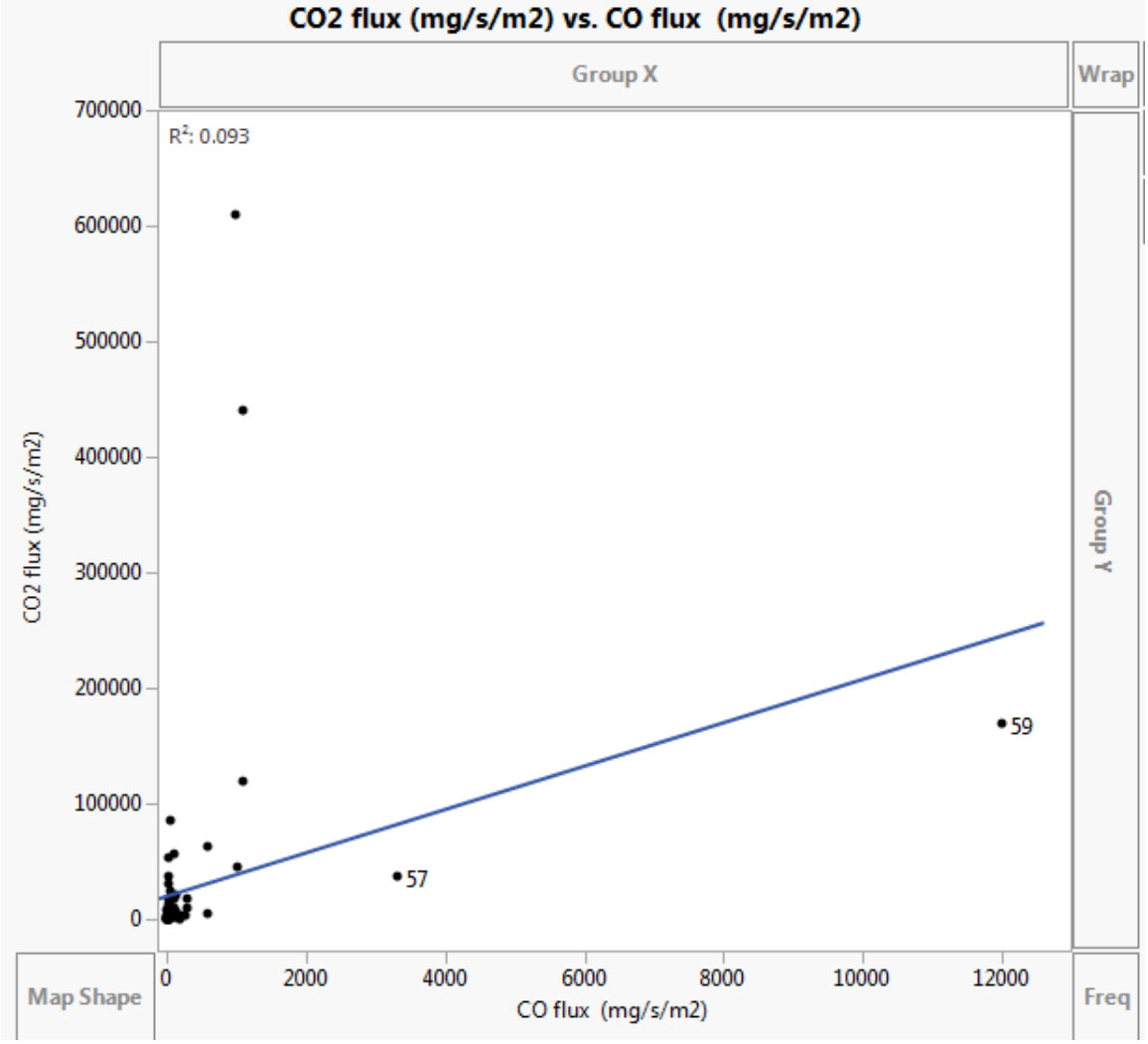
Appendix II – Parameters and R^2 values derived from comparing gaseous constituents from Appendix I using PCA (see Appendix III for Individual Charts).

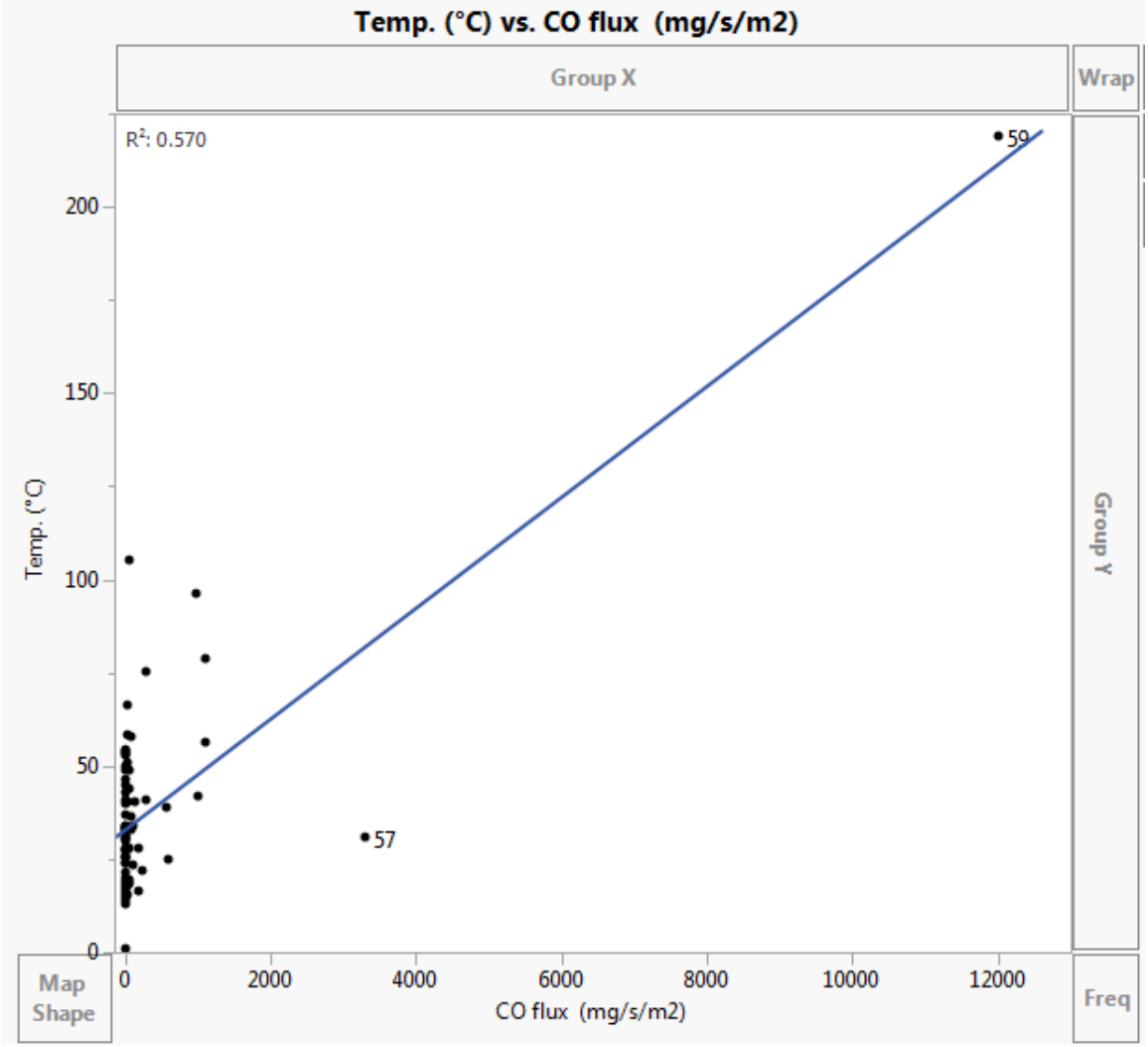
Parameters	R^2 Value (With Point 59)	R^2 Values (Without Point 59)	R^2 Values (Without top <u>two</u> values: 59 and 57)
CO vs. H_2S	0.979	0.799	0.449
CO vs. CH_4	0.052	0.744	0.333
CO vs. CO_2	0.093	0.196	0.501
CO vs. T	0.57	0.045	0.175
H_2S vs. CH_4	0.049	0.653	0.016
CO_2 vs. T	0.227	0.265	0.266
H_2S vs. T	0.51	0.001	0.052
CO_2 vs. CH_4	0.064	0.071	0.188
CH_4 vs. T	0.019	0.064	0.226
CO_2 vs. H_2S	0.047	0.014	0.184

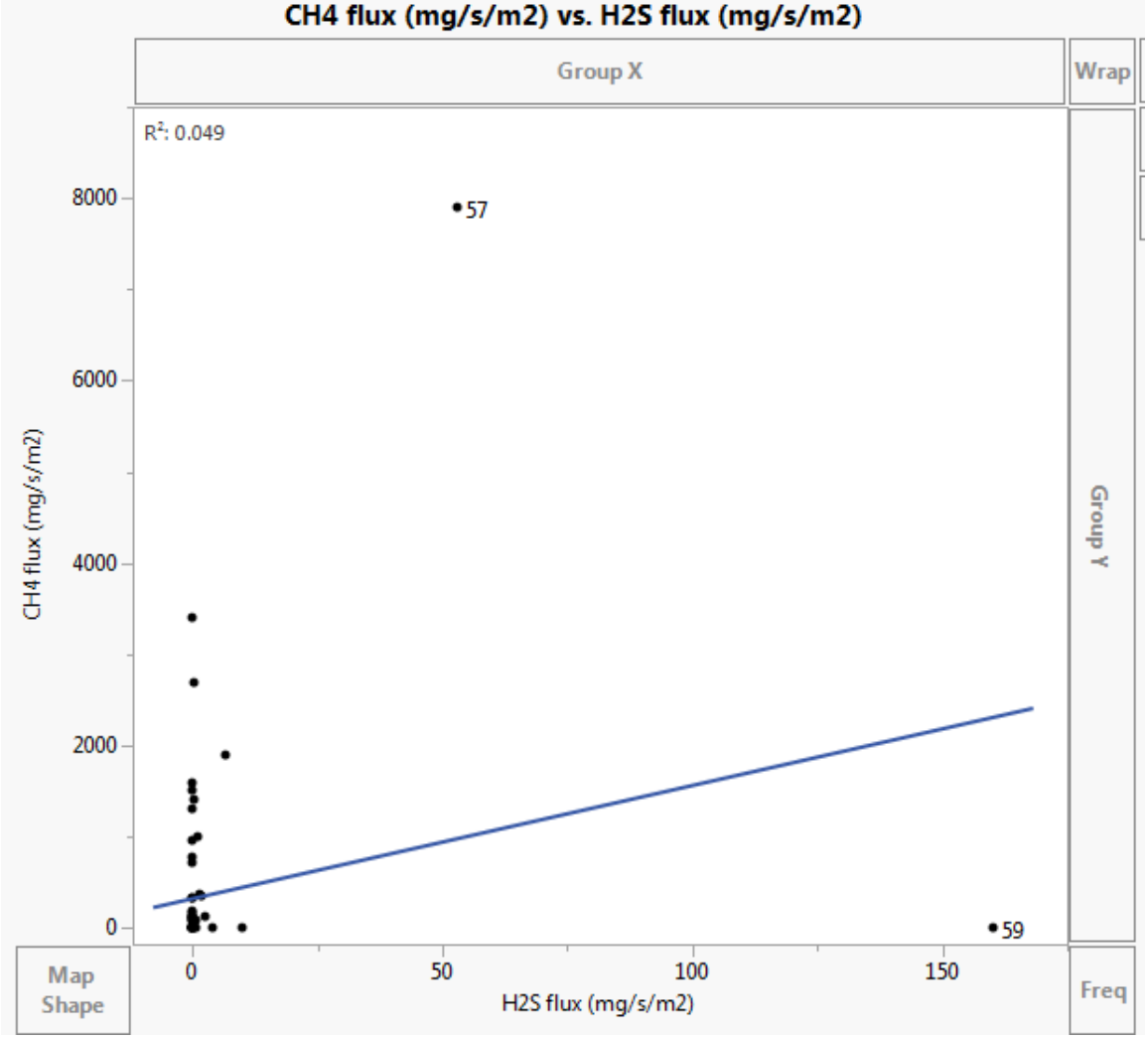
Appendix III – PCA JMP R^2 charts comparing gas relationships between parameters in Appendix II (With Points 57 and 59).

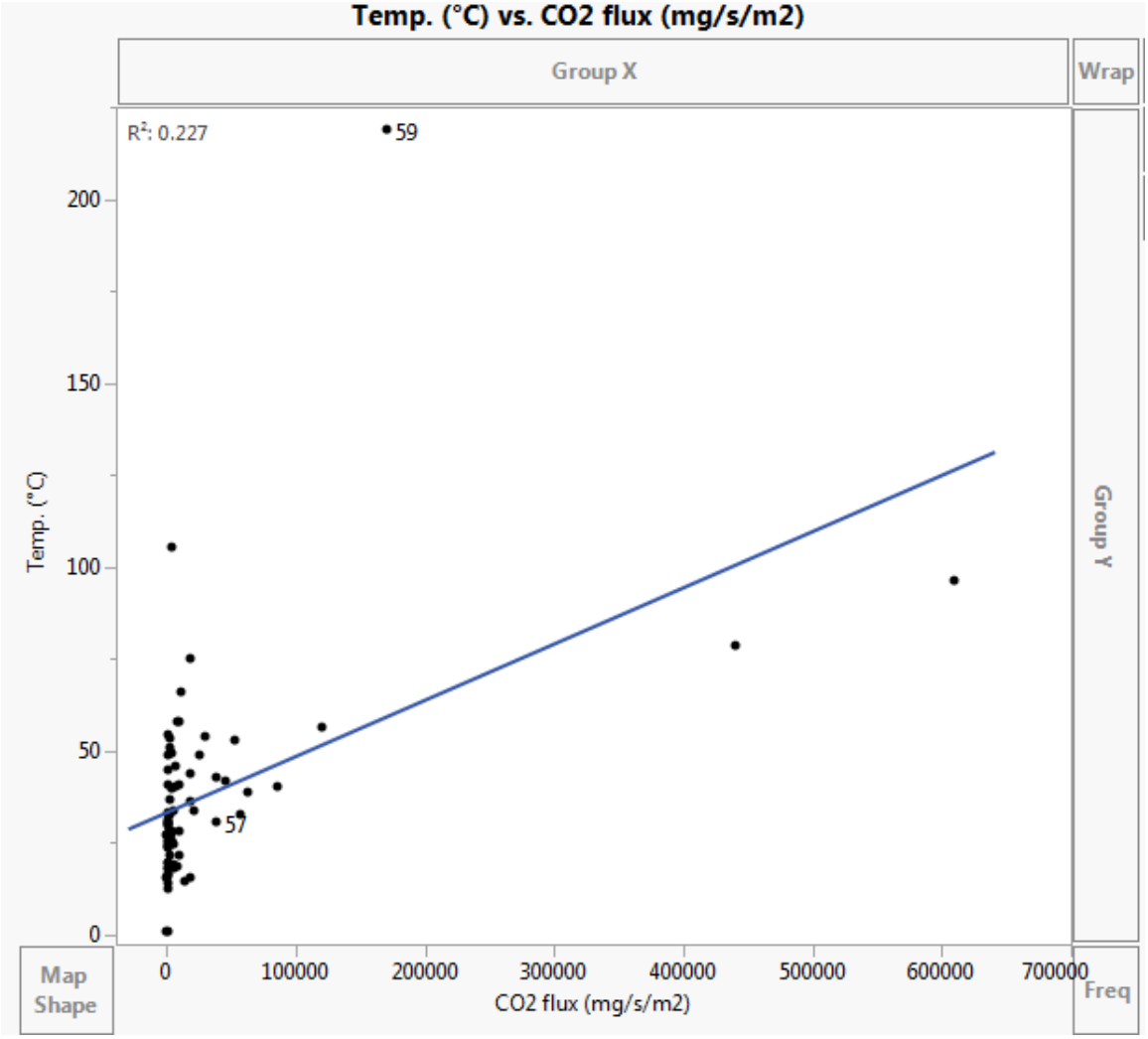


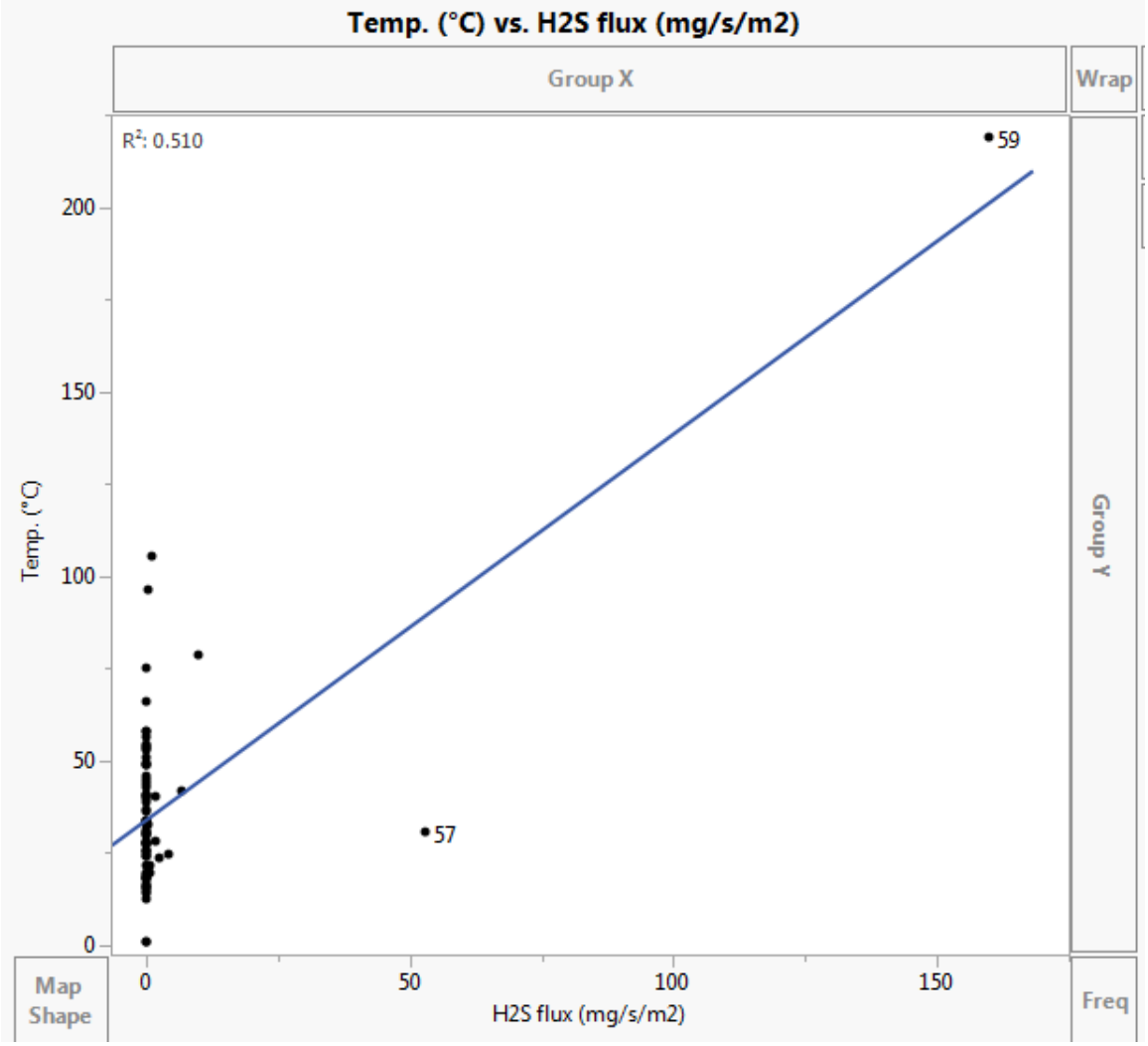

CH4 flux (mg/s/m2) vs. CO flux (mg/s/m2)
Group X
Wrap
R²: 0.052
57
59
8000
6000
4000
2000
0
CH4 flux (mg/s/m2)
Group Y
0
2000
4000
6000
8000
10000
12000
CO flux (mg/s/m2)
Map Shape
Freq

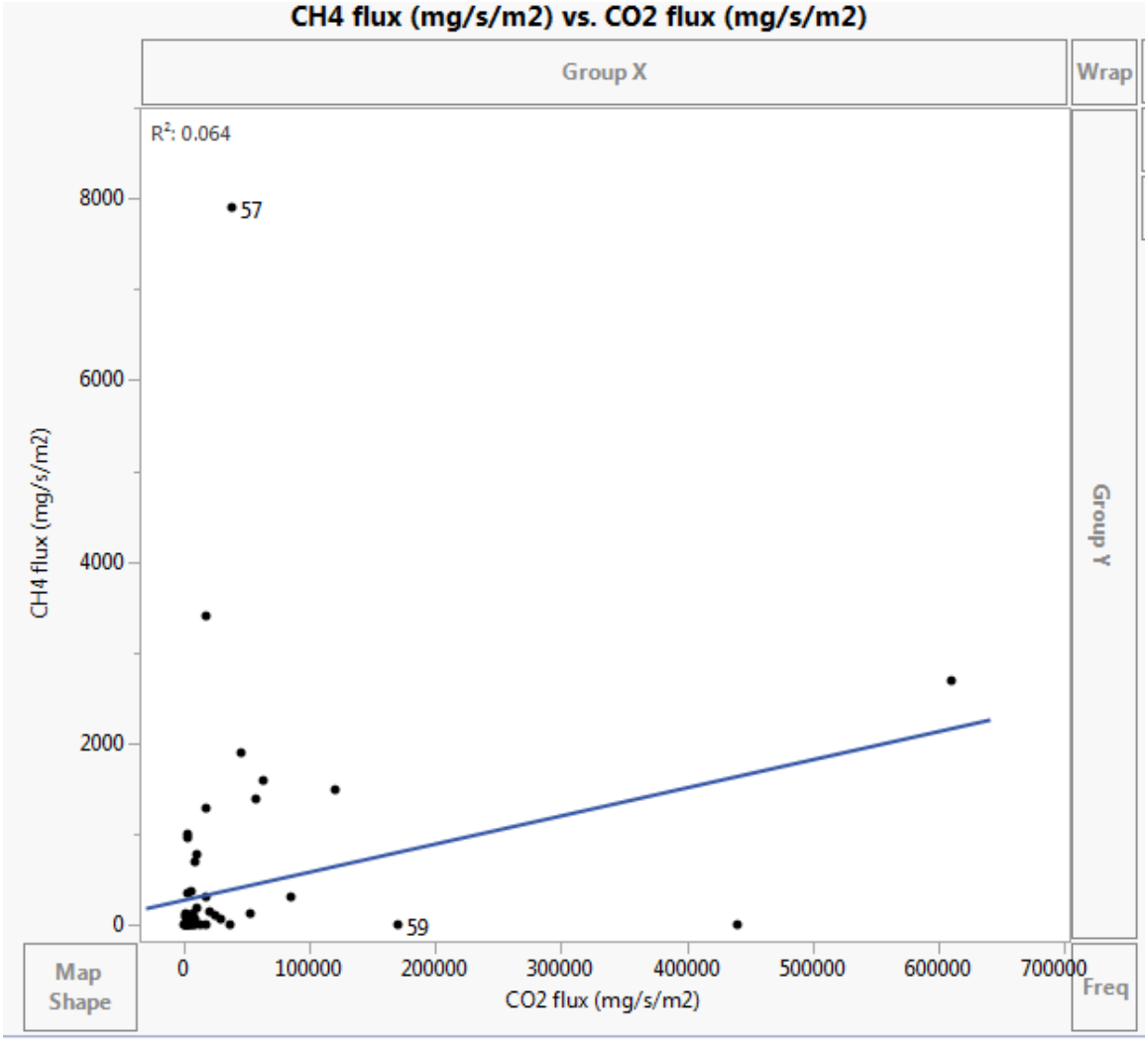

CO2 flux (mg/s/m2) vs. CO flux (mg/s/m2)
Group X
Wrap
R²: 0.093
700000
600000
500000
400000
300000
200000
100000
0
CO2 flux (mg/s/m2)
59
57
Group Y
Map Shape
0
2000
4000
6000
8000
10000
12000
CO flux (mg/s/m2)
Freq

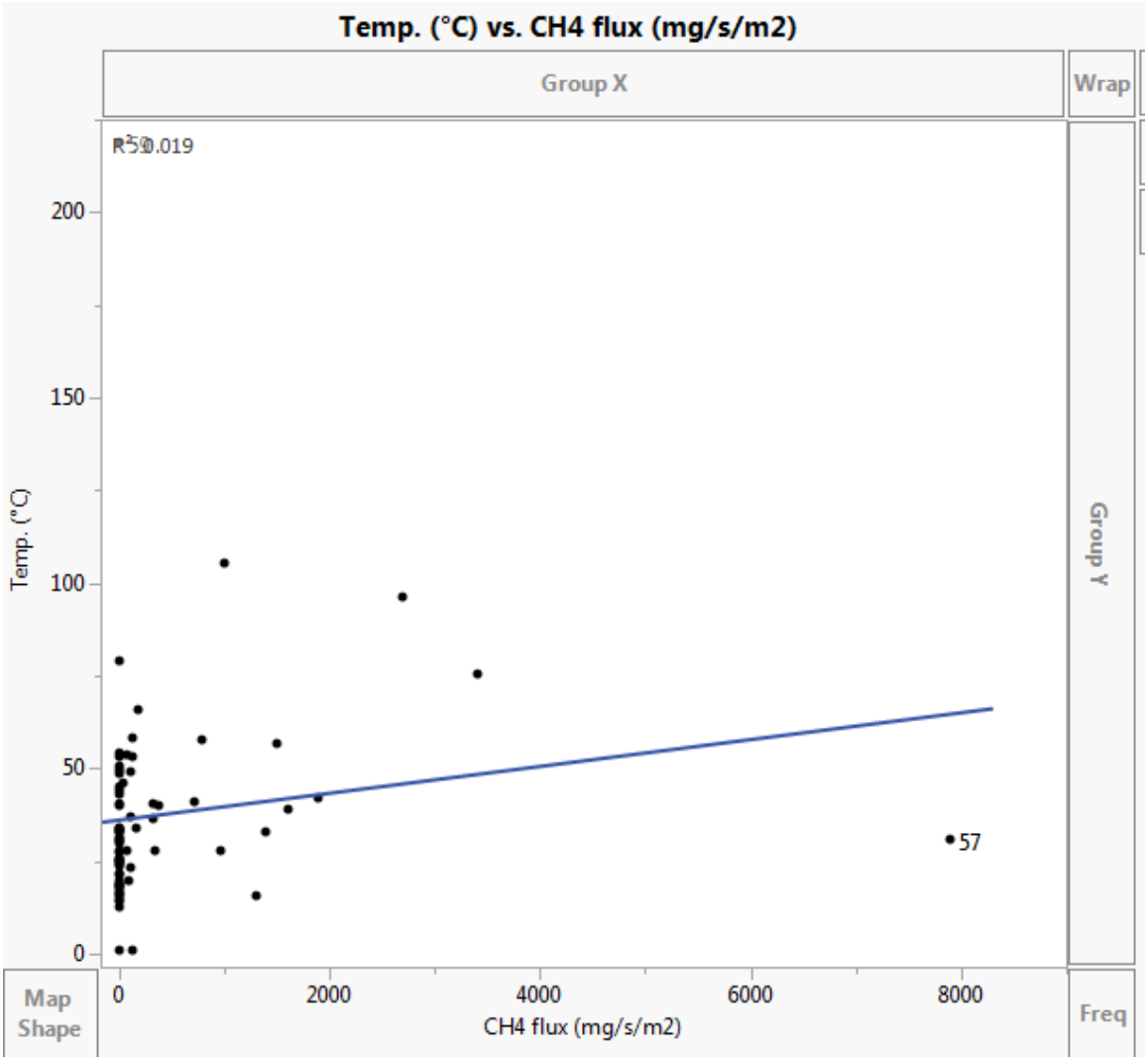

Temp. (°C) vs. CO flux (mg/s/m2)
Group X
Wrap
R²: 0.570
59
57
200
150
100
50
0
Temp. (°C)
Group Y
Map Shape
0
2000
4000
6000
8000
10000
12000
CO flux (mg/s/m2)
Freq

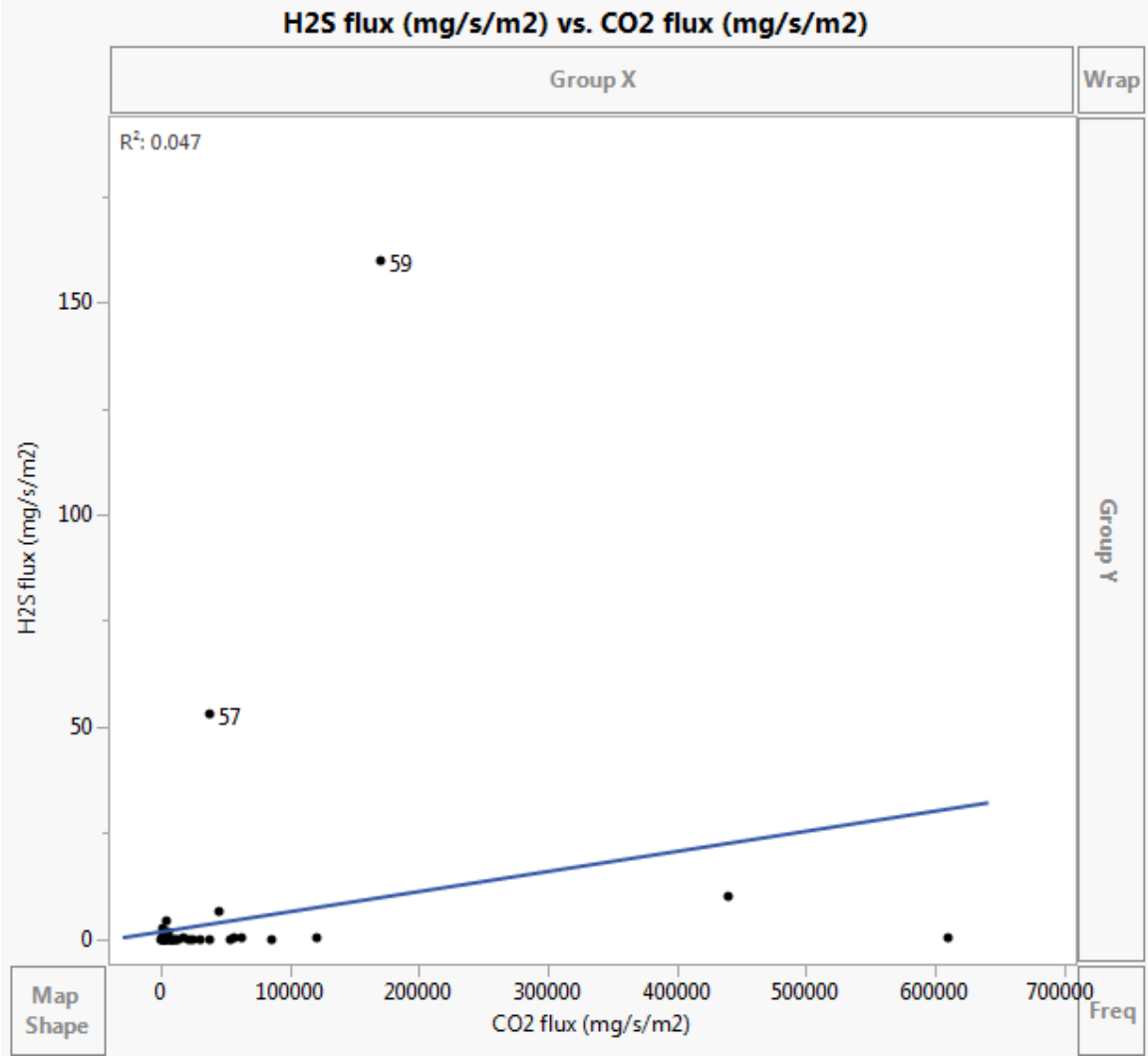

CH4 flux (mg/s/m2) vs. H2S flux (mg/s/m2)
Group X
Wrap
R²: 0.049
8000
6000
4000
2000
0
57
59
CH4 flux (mg/s/m2)
Group Y
Map Shape
0
50
100
150
H2S flux (mg/s/m2)
Freq


Temp. (°C) vs. CO2 flux (mg/s/m2)
Group X
Wrap
R²: 0.227
59
57
200
150
100
50
0
Temp. (°C)
Group Y
Map Shape
0
100000
200000
300000
400000
500000
600000
700000
CO2 flux (mg/s/m2)
Freq

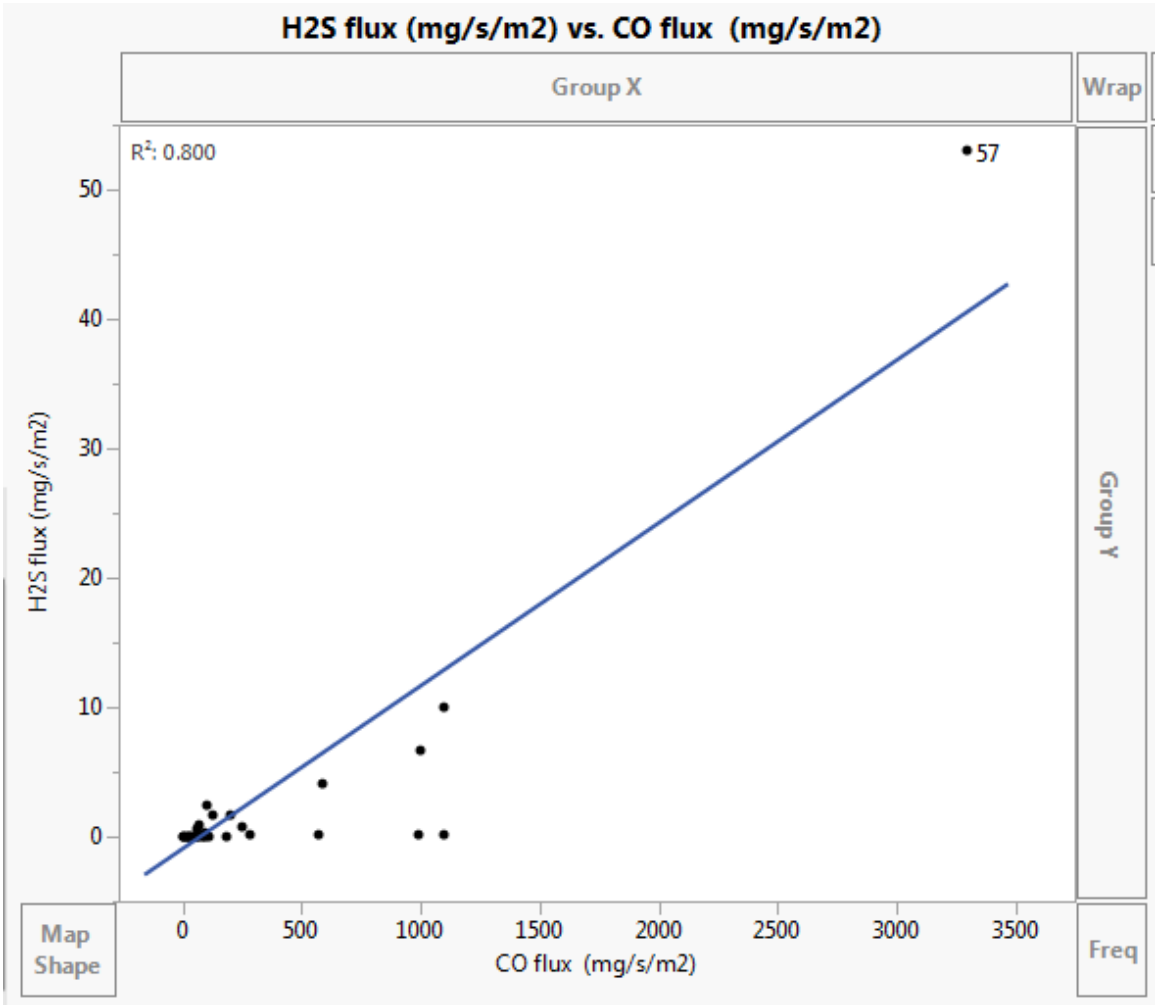

Temp. (°C) vs. H2S flux (mg/s/m2)
Group X
Wrap
R²: 0.510
59
57
200
150
100
50
0
Temp. (°C)
Group Y
Map Shape
0
50
100
150
H2S flux (mg/s/m2)
Freq

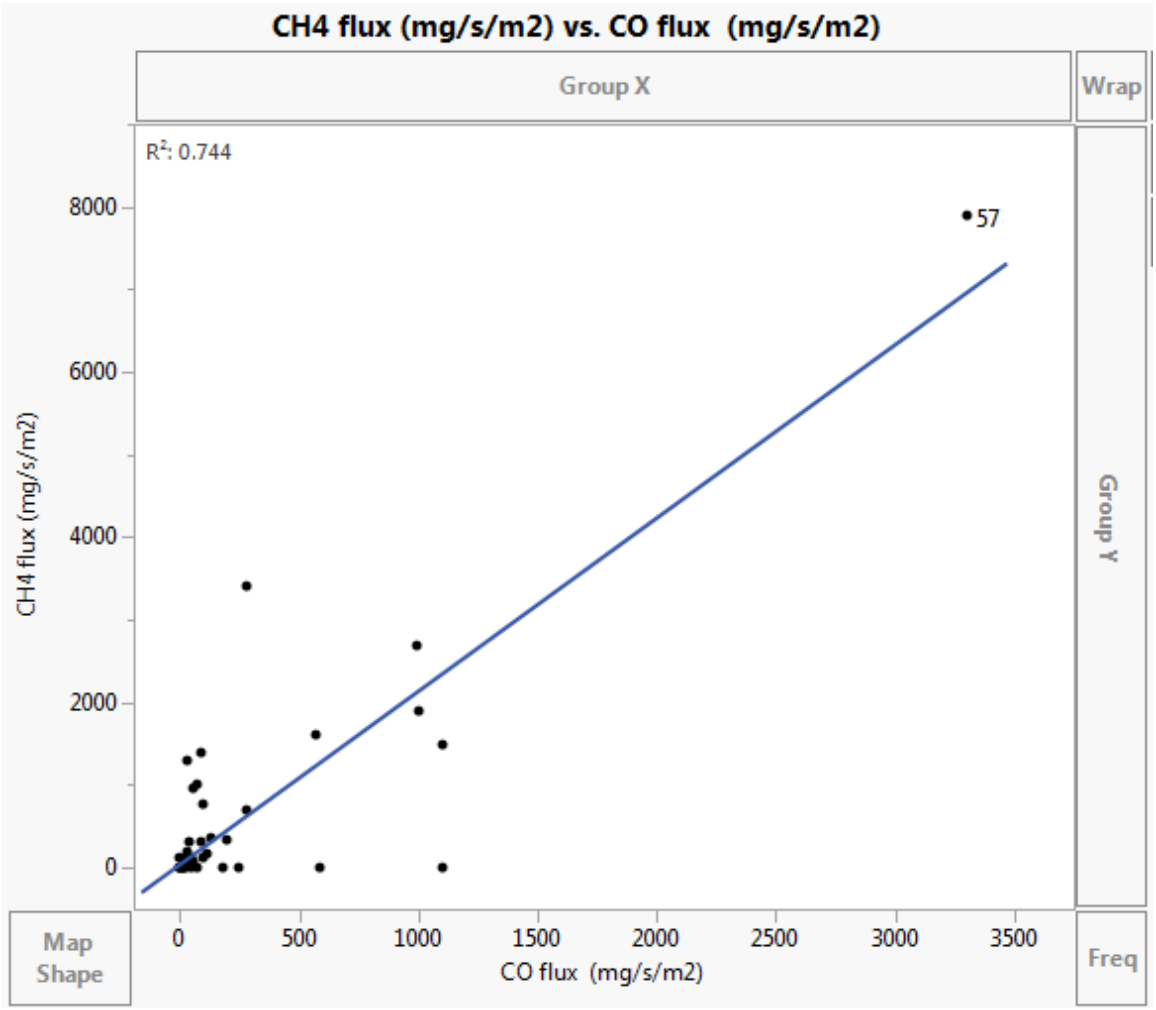

CH4 flux (mg/s/m2) vs. CO2 flux (mg/s/m2)
Group X
Wrap
R²: 0.064
8000
6000
4000
2000
0
57
59
CH4 flux (mg/s/m2)
Group Y
Map Shape
0
100000
200000
300000
400000
500000
600000
700000
CO2 flux (mg/s/m2)
Freq

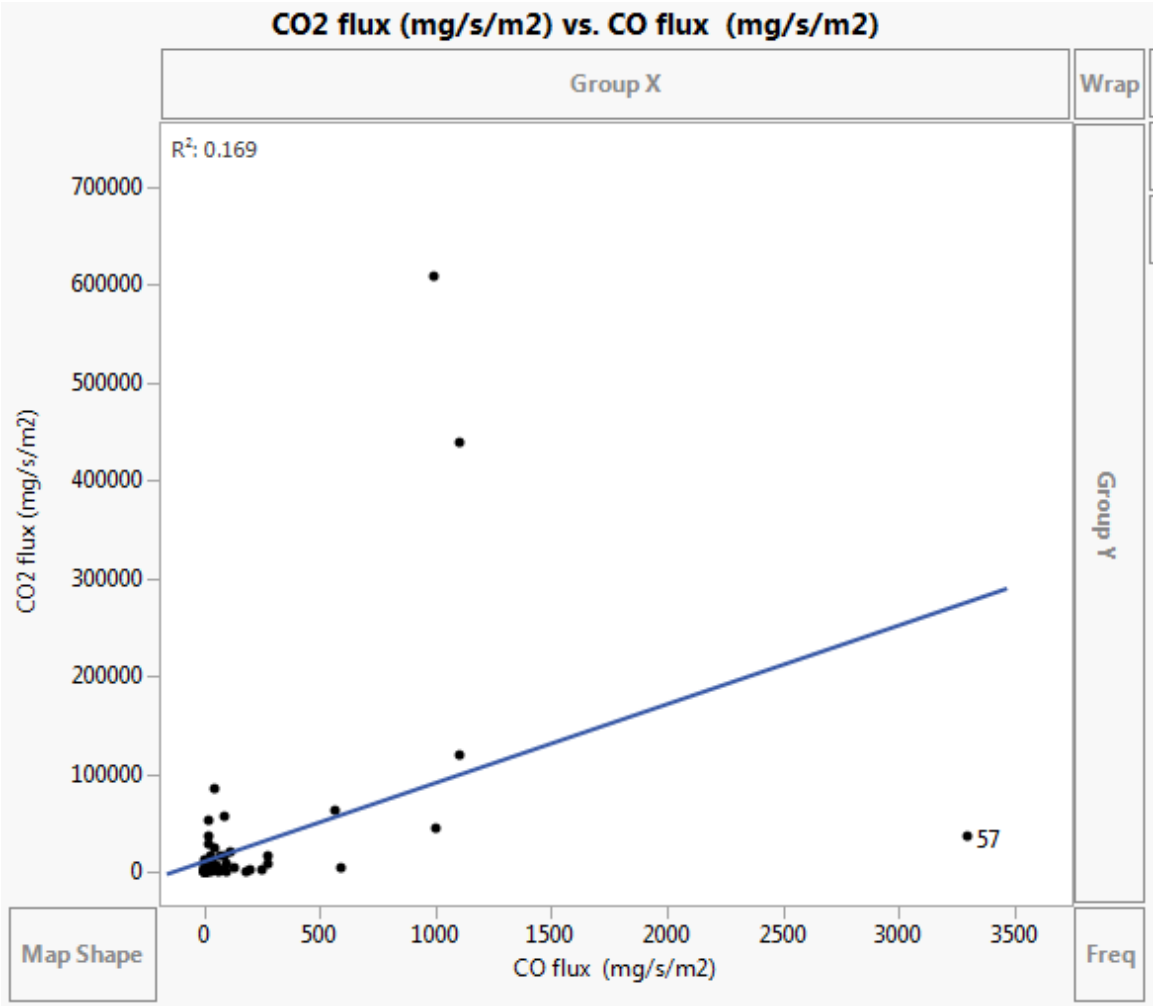

Temp. (°C) vs. CH4 flux (mg/s/m2)
Group X
Wrap
R²0.019
200
150
100
50
0
Temp. (°C)
57
Group Y
Map Shape
0
2000
4000
6000
8000
CH4 flux (mg/s/m2)
Freq

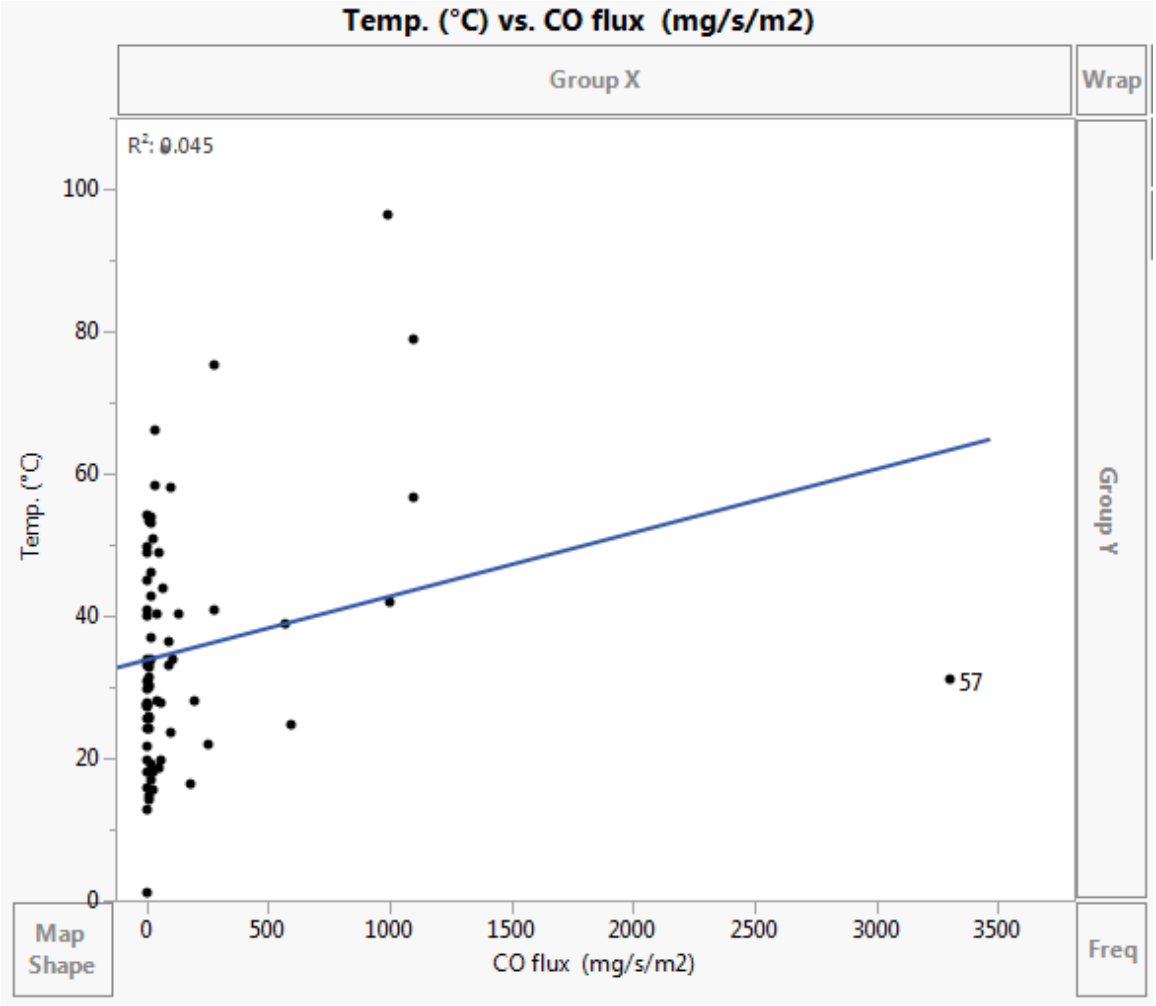

H2S flux (mg/s/m2) vs. CO2 flux (mg/s/m2)
Group X
Wrap
R²: 0.047
59
57
150
100
50
0
H2S flux (mg/s/m2)
Group Y
Map Shape
0
100000
200000
300000
400000
500000
600000
700000
CO2 flux (mg/s/m2)
Freq

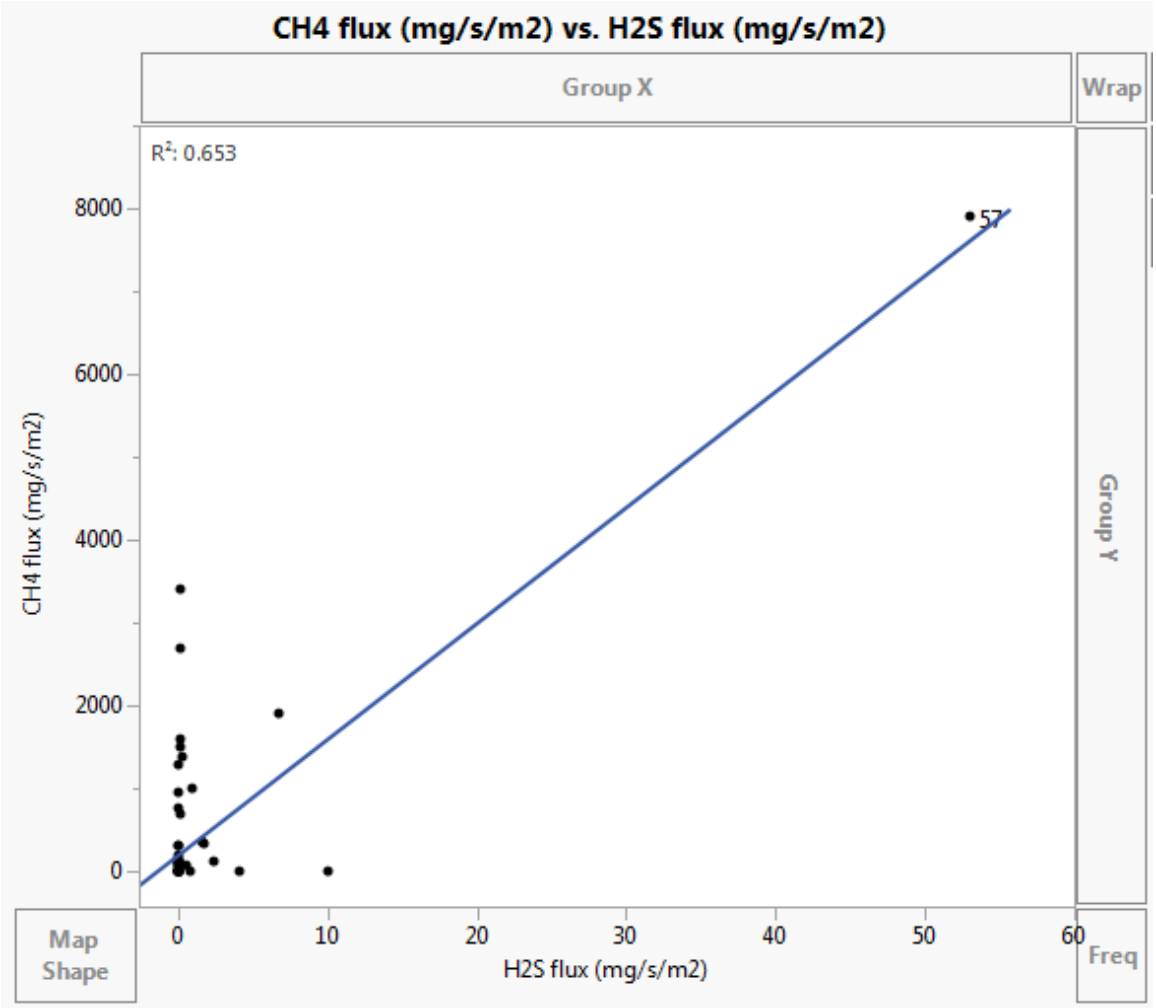
PCA JMP R^2 charts comparing gas relationships between parameters in Appendix II (without Point 59).

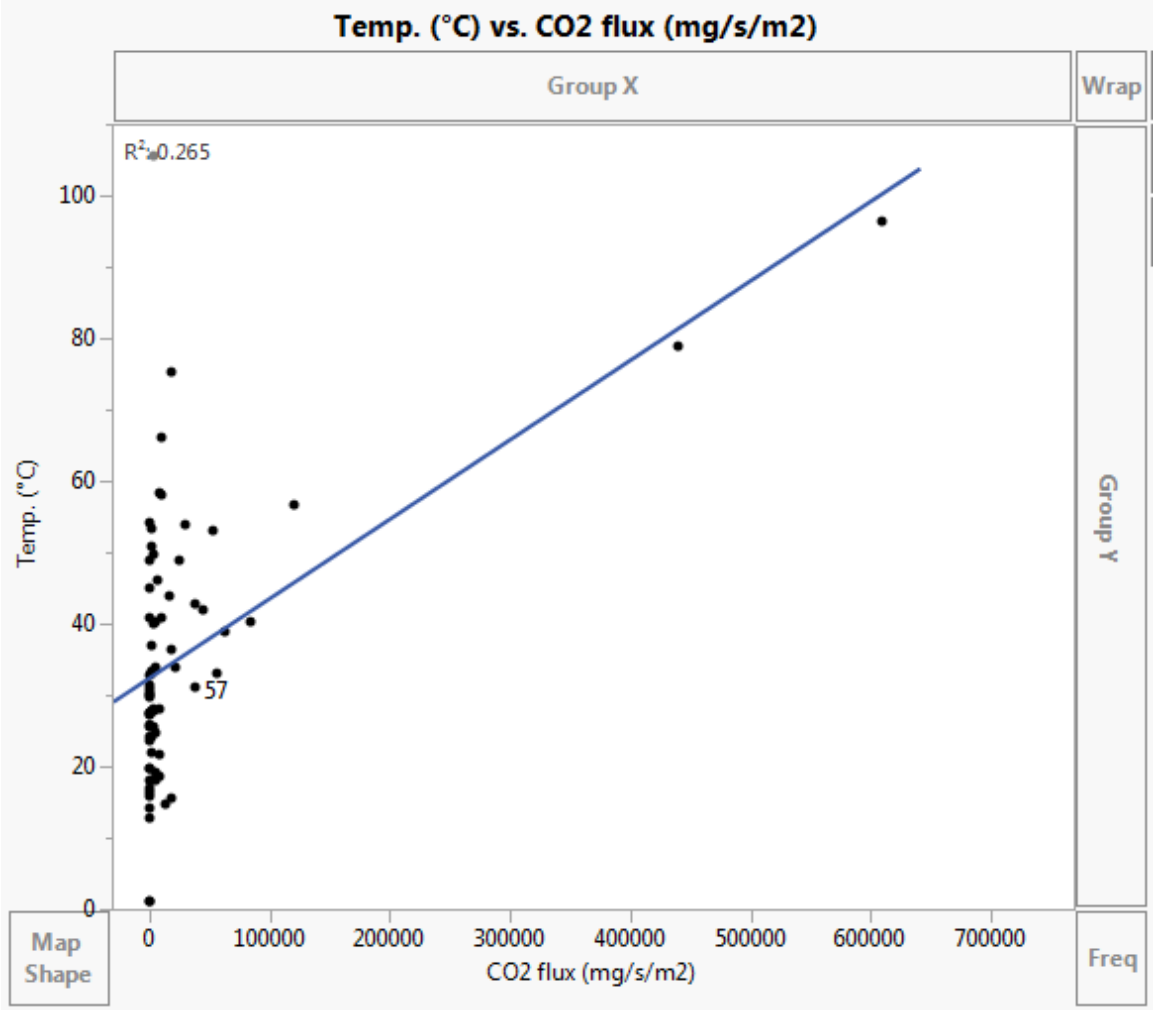


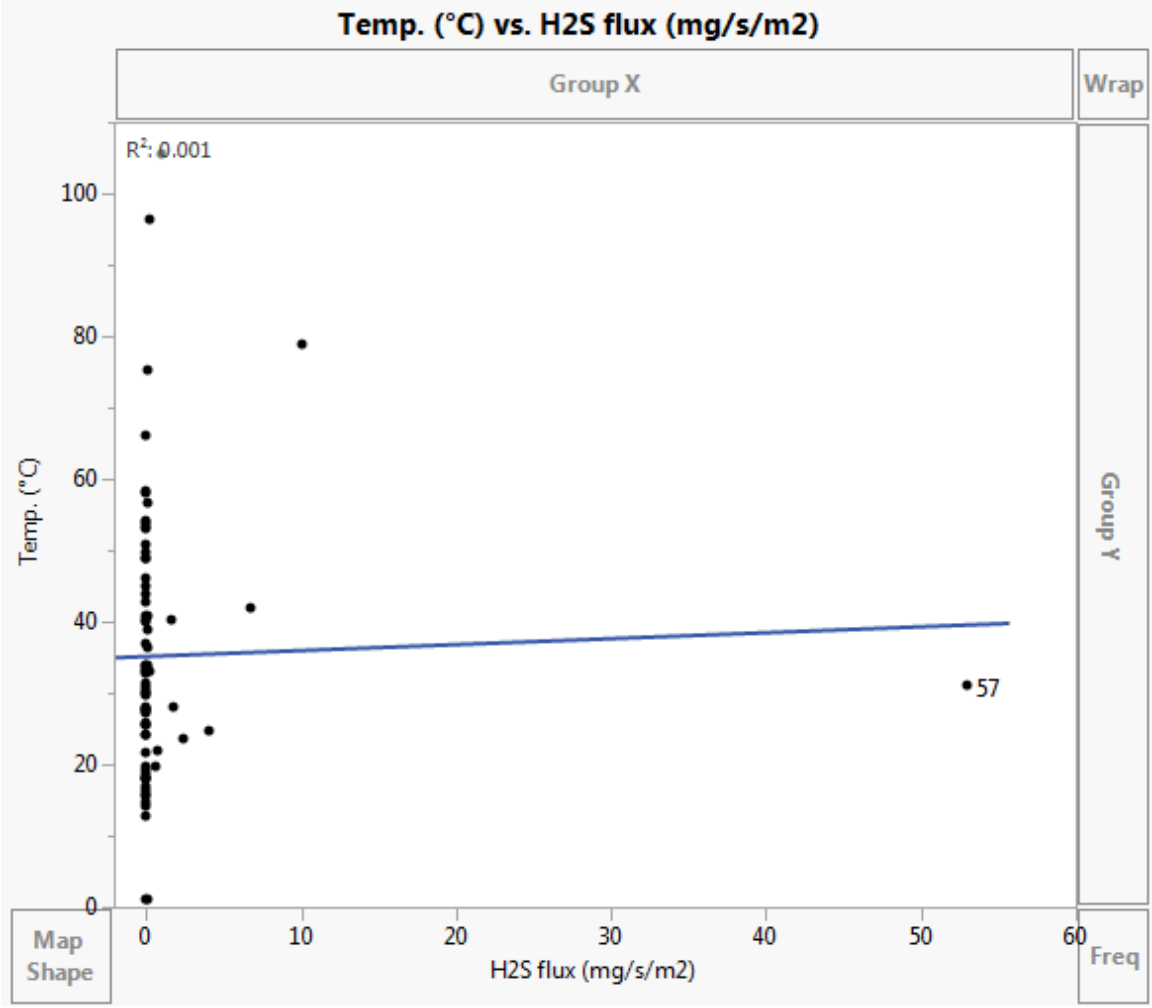

CH4 flux (mg/s/m2) vs. CO flux (mg/s/m2)
Group X
Wrap
R²: 0.744
57
8000
6000
4000
2000
0
CH4 flux (mg/s/m2)
Group Y
Map Shape
0
500
1000
1500
2000
2500
3000
3500
CO flux (mg/s/m2)
Freq

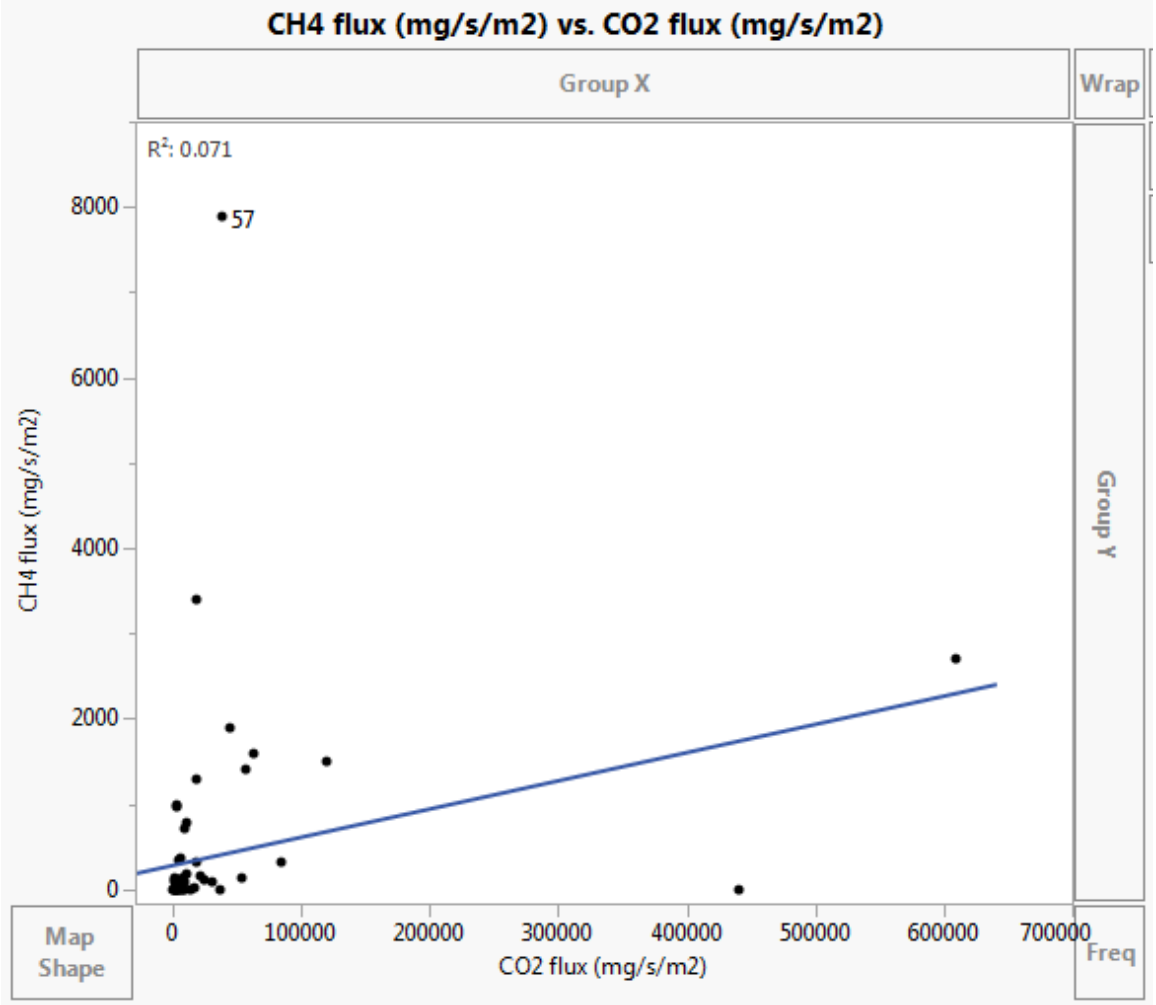

CO2 flux (mg/s/m2) vs. CO flux (mg/s/m2)
Group X
Wrap
R²: 0.169
700000
600000
500000
400000
300000
200000
100000
0
CO2 flux (mg/s/m2)
57
Group Y
Map Shape
0
500
1000
1500
2000
2500
3000
3500
CO flux (mg/s/m2)
Freq

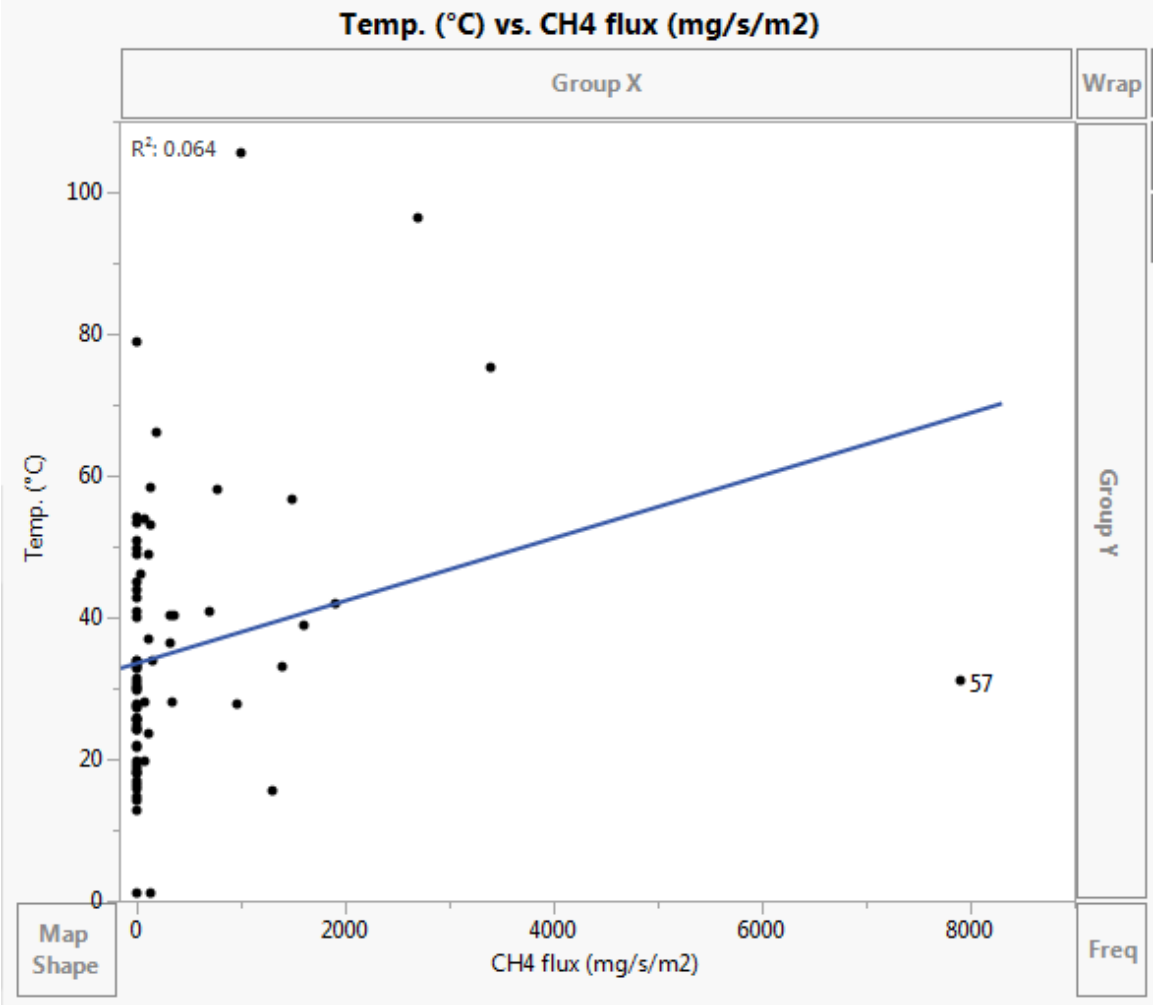

Temp. (°C) vs. CO flux (mg/s/m2)
Group X
Wrap
R²: 0.045
100
80
60
40
20
0
Temp. (°C)
57
Group Y
Map Shape
0
500
1000
1500
2000
2500
3000
3500
CO flux (mg/s/m2)
Freq

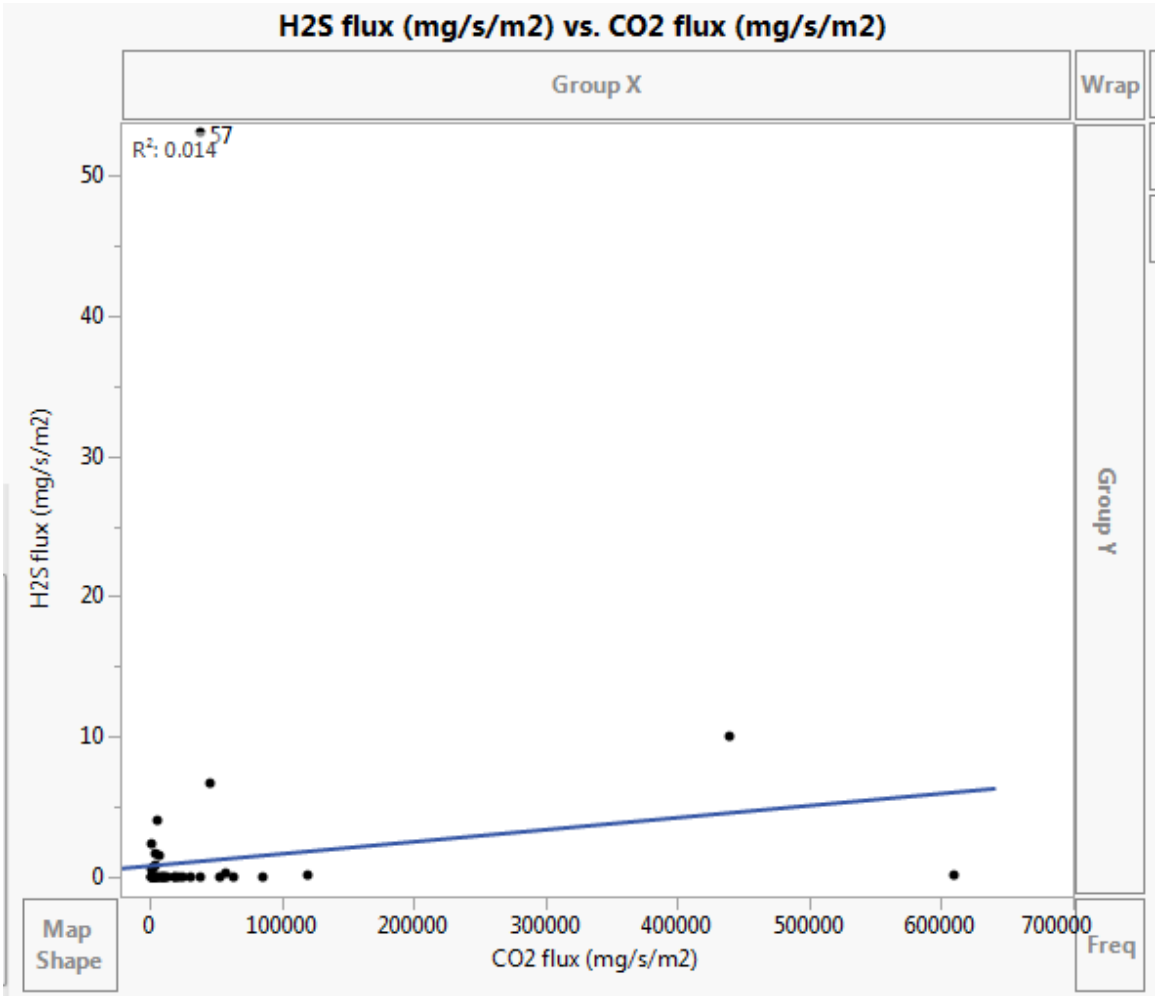

CH4 flux (mg/s/m2) vs. H2S flux (mg/s/m2)
Group X
Wrap
R²: 0.653
57
8000
6000
4000
2000
0
CH4 flux (mg/s/m2)
Group Y
Map Shape
0
10
20
30
40
50
60
H2S flux (mg/s/m2)
Freq


Temp. (°C) vs. CO2 flux (mg/s/m2)
Group X
Wrap
R²=0.265
100
80
60
40
20
0
Temp. (°C)
57
Group Y
Map Shape
0
100000
200000
300000
400000
500000
600000
700000
CO2 flux (mg/s/m2)
Freq

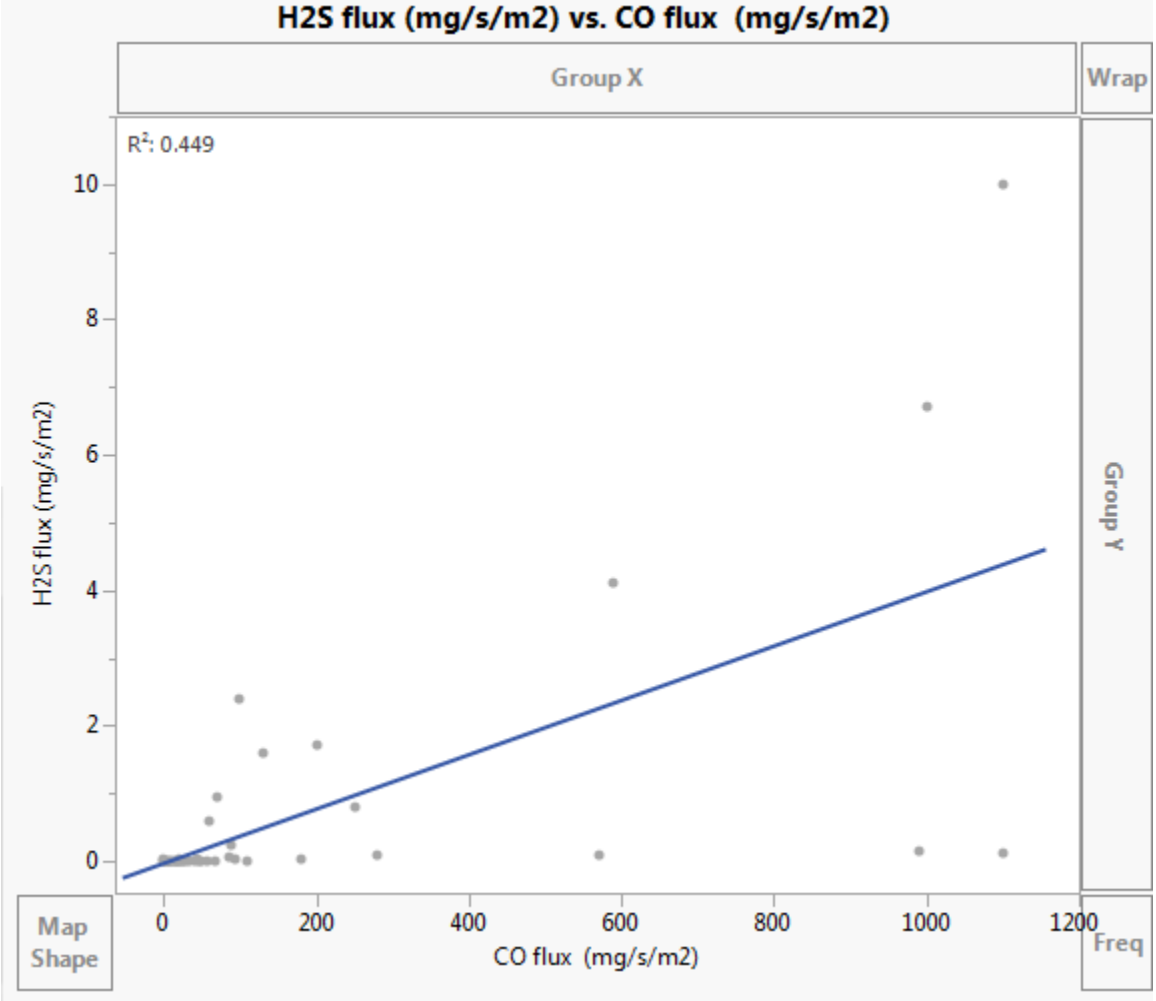

Temp. (°C) vs. H2S flux (mg/s/m2)
Group X
Wrap
R²: 0.001
100
80
60
40
20
0
Temp. (°C)
57
Group Y
Map Shape
0
10
20
30
40
50
60
H2S flux (mg/s/m2)
Freq

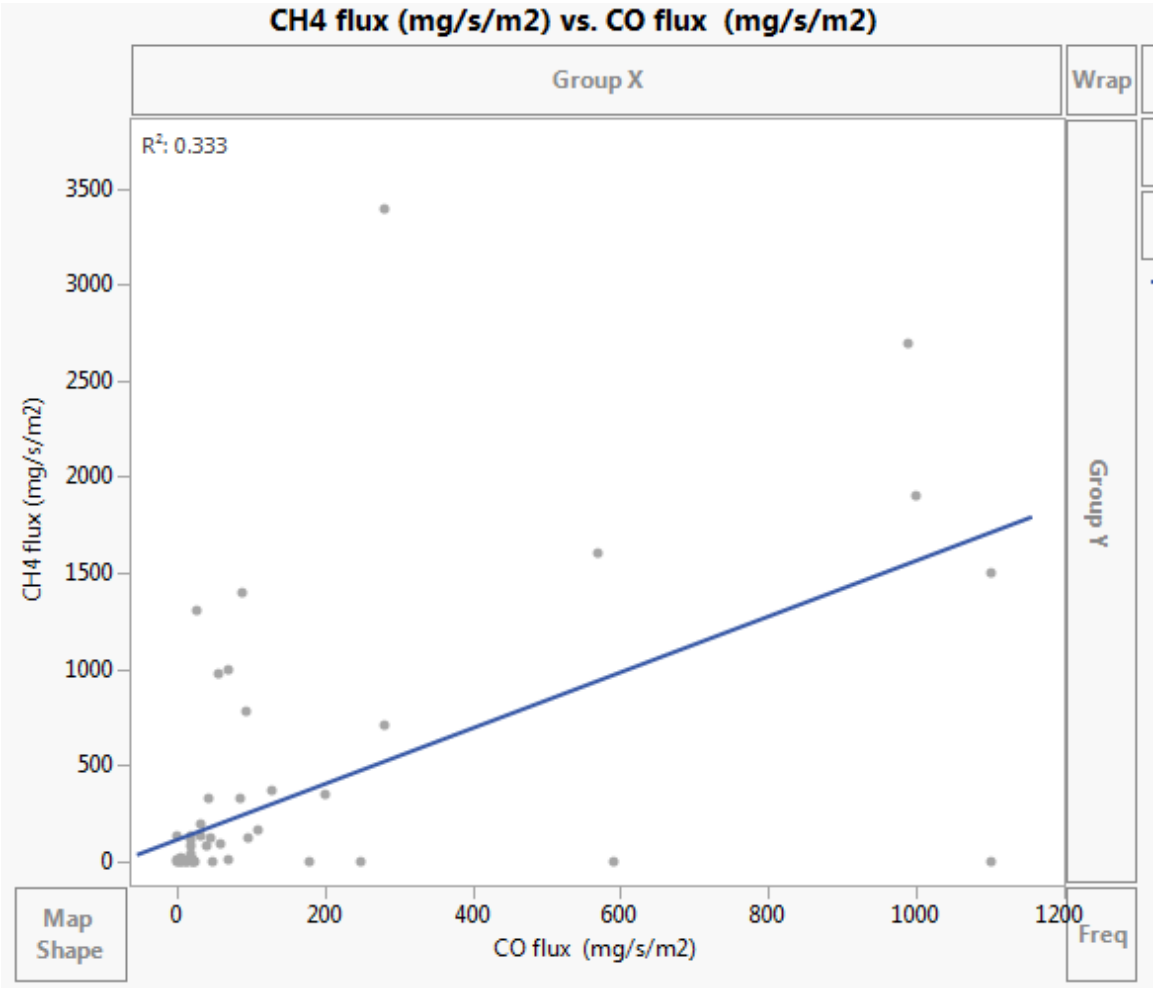

CH4 flux (mg/s/m2) vs. CO2 flux (mg/s/m2)
Group X
Wrap
R²: 0.071
57
8000
6000
4000
2000
0
CH4 flux (mg/s/m2)
Group Y
Map Shape
0
100000
200000
300000
400000
500000
600000
700000
CO2 flux (mg/s/m2)
Freq

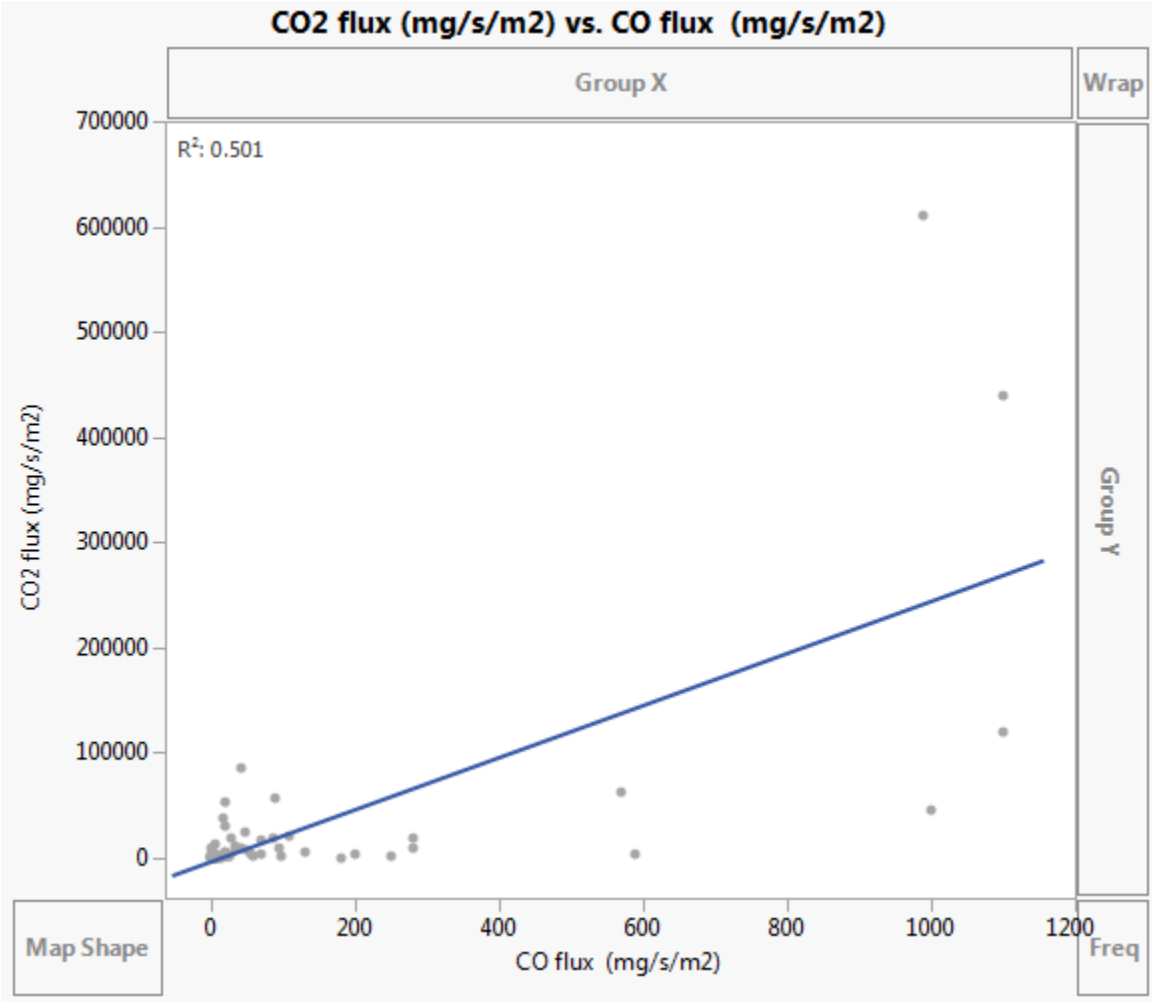

Temp. (°C) vs. CH4 flux (mg/s/m2)
Group X
Wrap
R²: 0.064
100
80
60
40
20
0
Temp. (°C)
57
Group Y
Map Shape
0
2000
4000
6000
8000
CH4 flux (mg/s/m2)
Freq

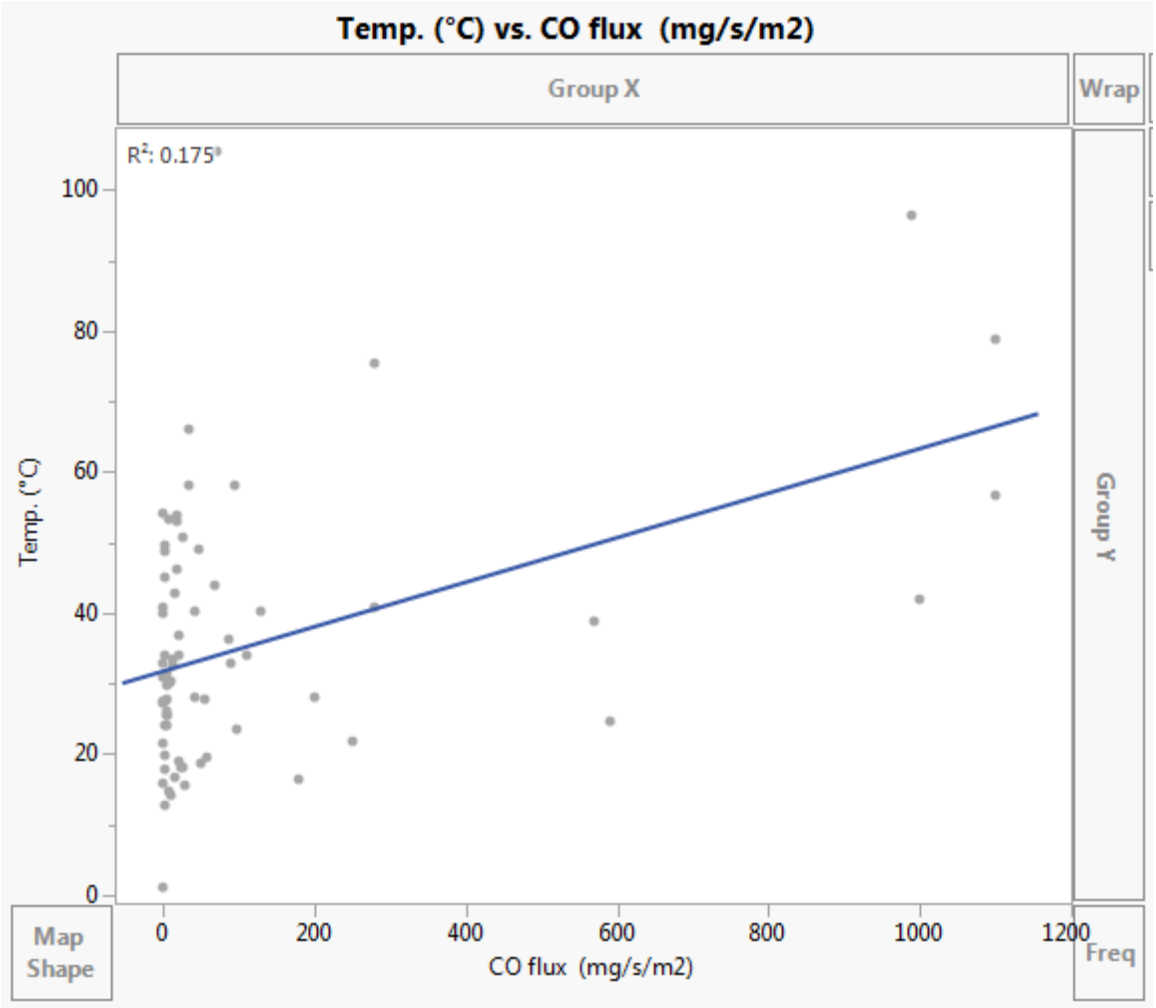

H2S flux (mg/s/m2) vs. CO2 flux (mg/s/m2)
Group X
Wrap
R²: 0.014
57
50
40
30
20
10
0
H2S flux (mg/s/m2)
Group Y
Map Shape
0
100000
200000
300000
400000
500000
600000
700000
CO2 flux (mg/s/m2)
Freq

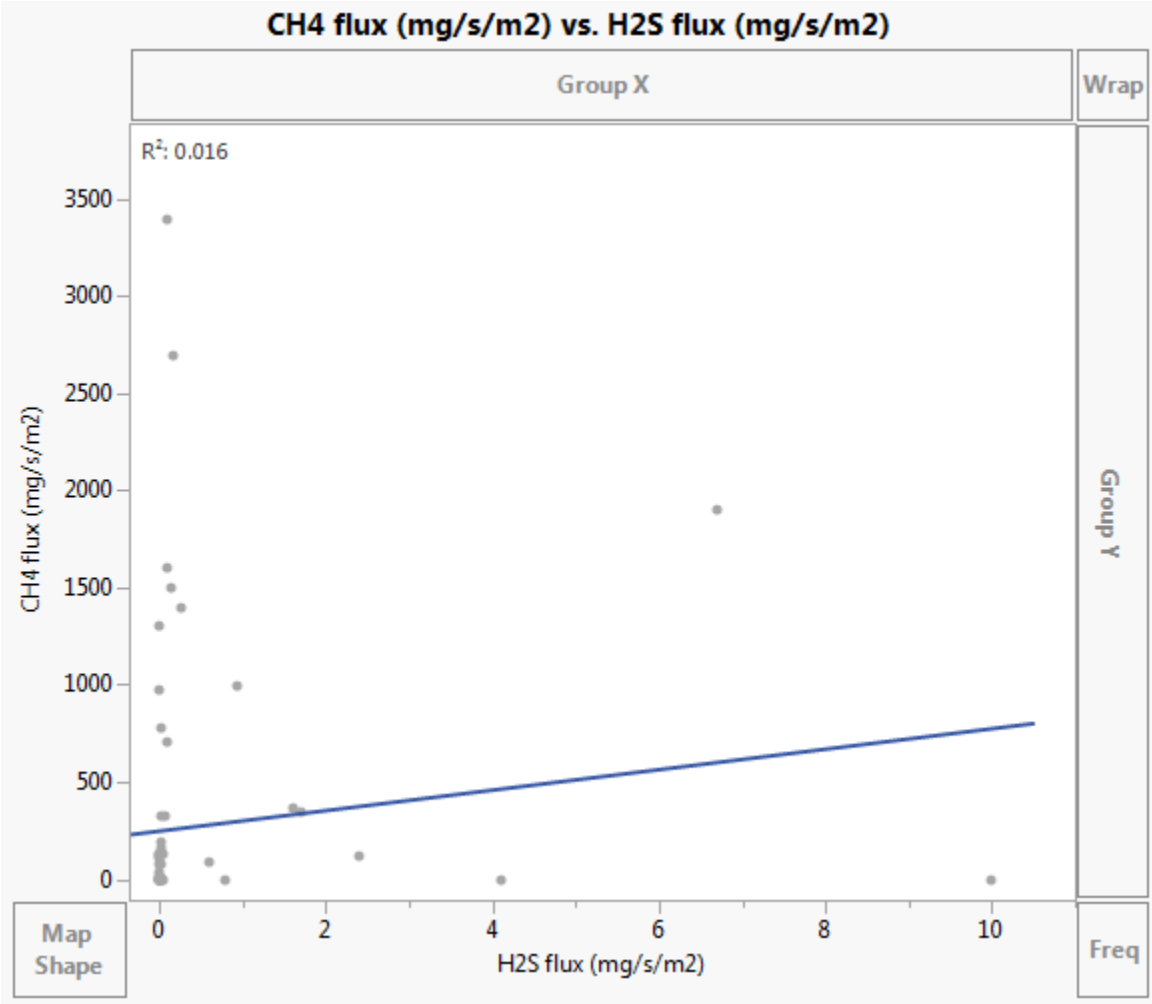
PCA JMP R^2 charts comparing gas relationships between parameters in Appendix II (without points 57 and 59)

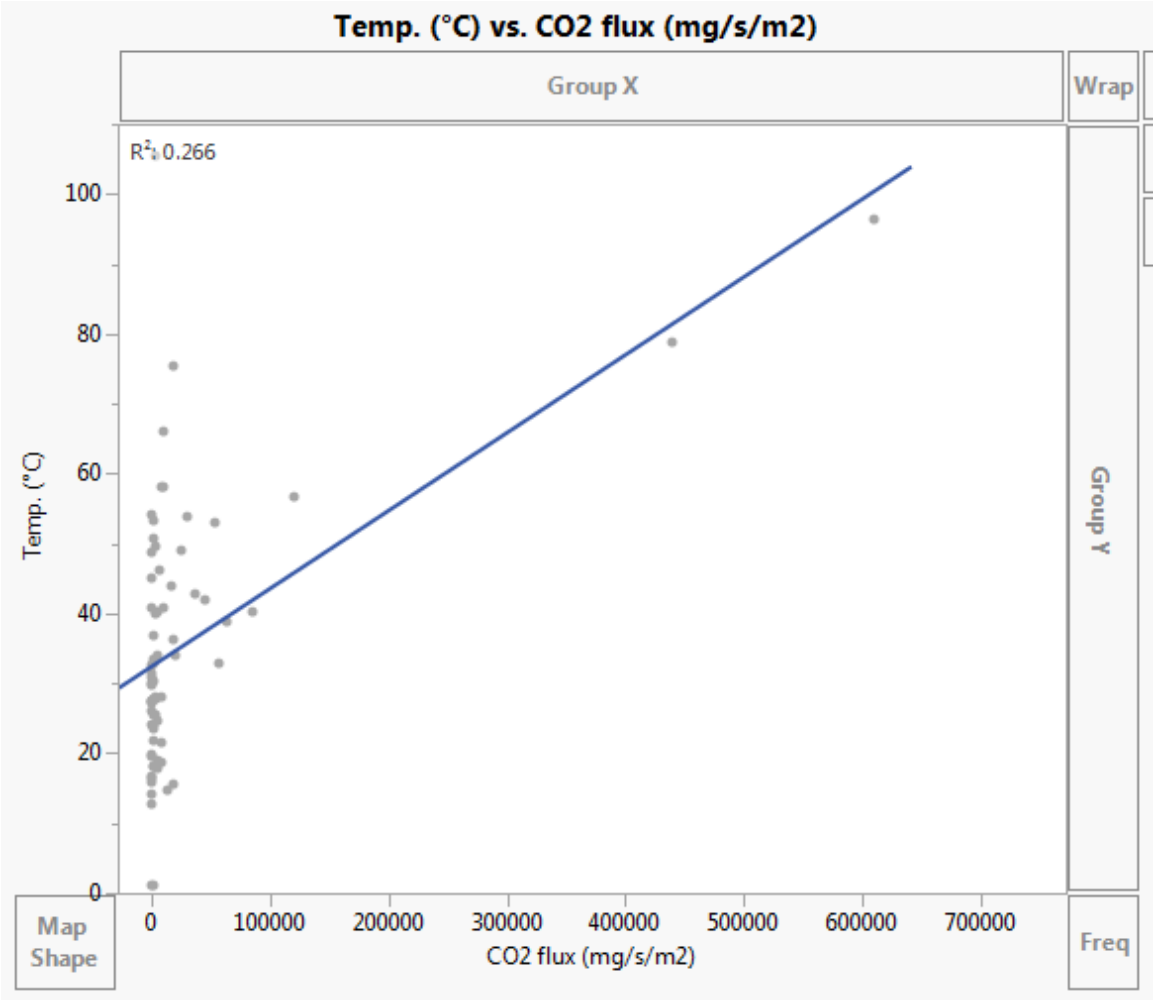


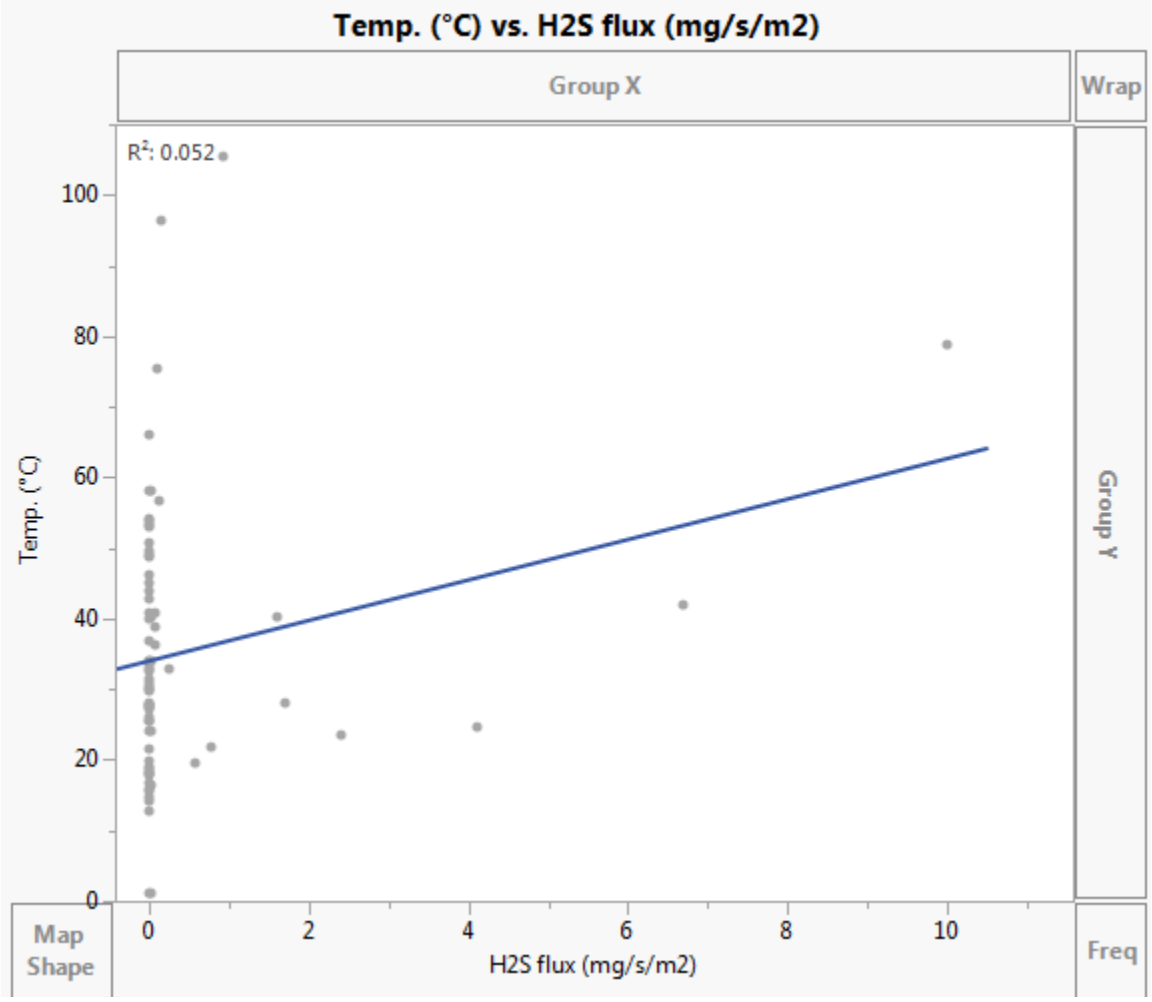

CH4 flux (mg/s/m2) vs. CO flux (mg/s/m2)
Group X
Wrap
R²: 0.333
3500
3000
2500
2000
1500
1000
500
0
CH4 flux (mg/s/m2)
Group Y
Map Shape
0
200
400
600
800
1000
1200
CO flux (mg/s/m2)
Freq

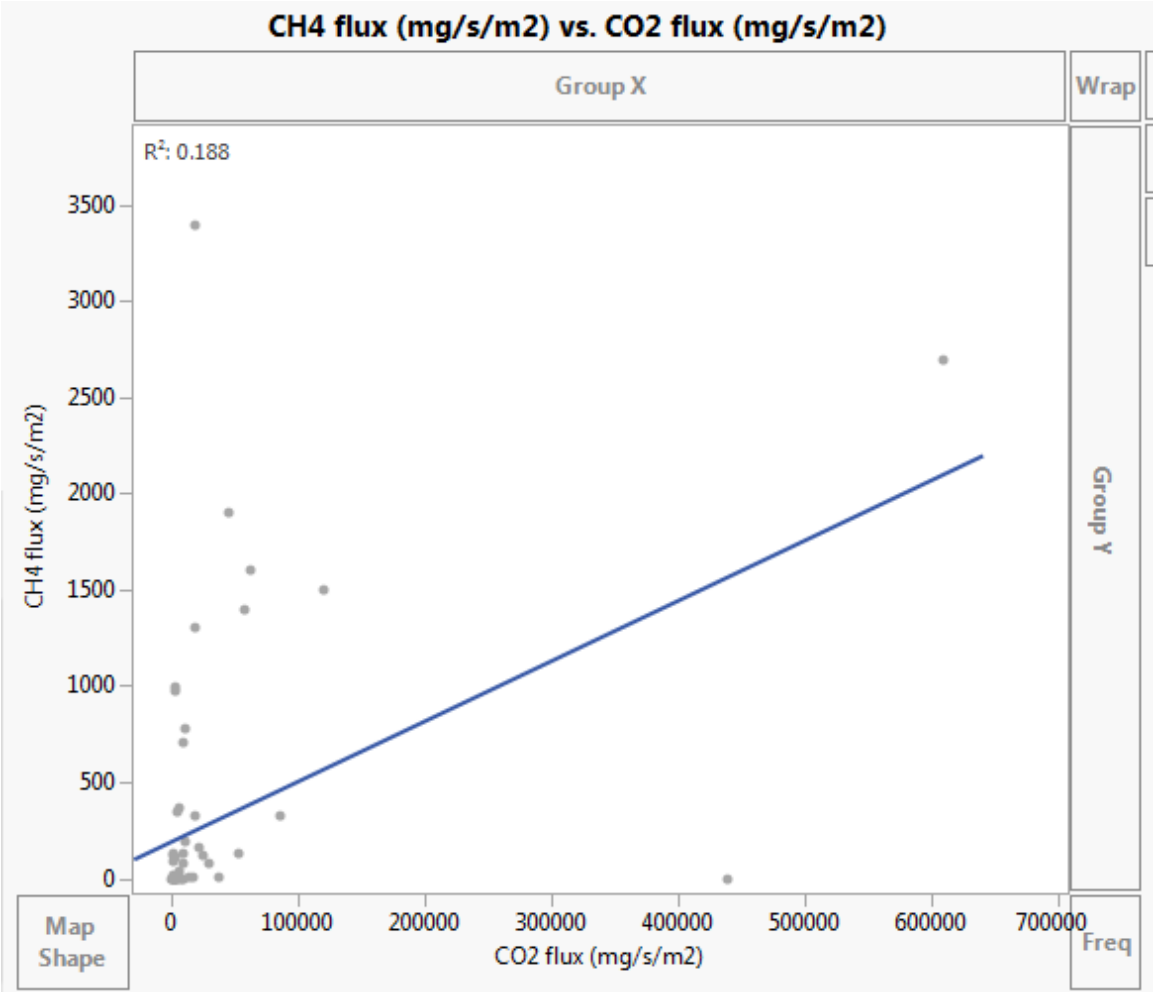

CO2 flux (mg/s/m2) vs. CO flux (mg/s/m2)
Group X
Wrap
Group Y
Freq
Map Shape
R²: 0.501
CO2 flux (mg/s/m2)
CO flux (mg/s/m2)
700000
600000
500000
400000
300000
200000
100000
0
0
200
400
600
800
1000
1200

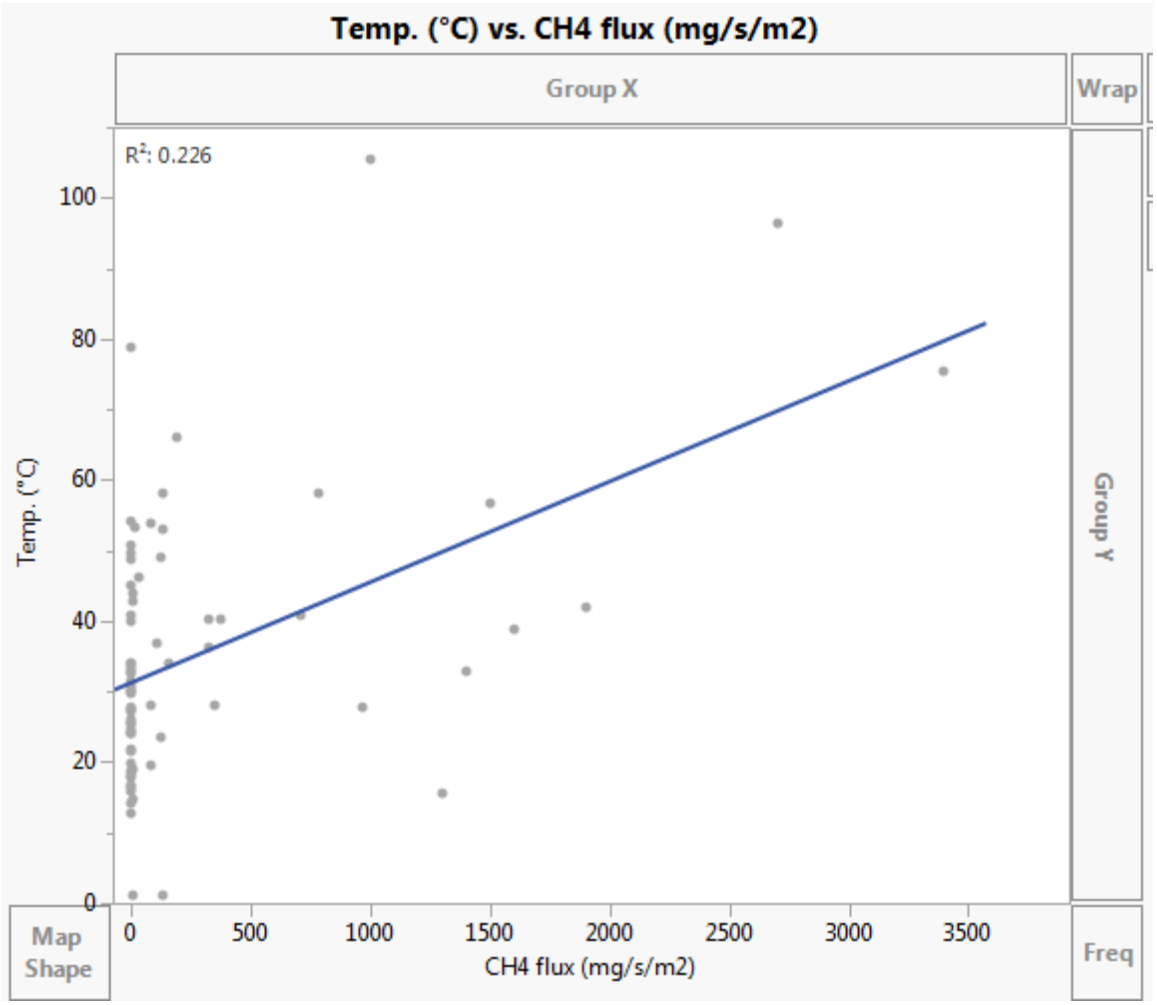

Temp. (°C) vs. CO flux (mg/s/m2)
Group X
Wrap
R²: 0.175
100
80
60
40
20
0
Temp. (°C)
Group Y
Map Shape
0
200
400
600
800
1000
1200
CO flux (mg/s/m2)
Freq

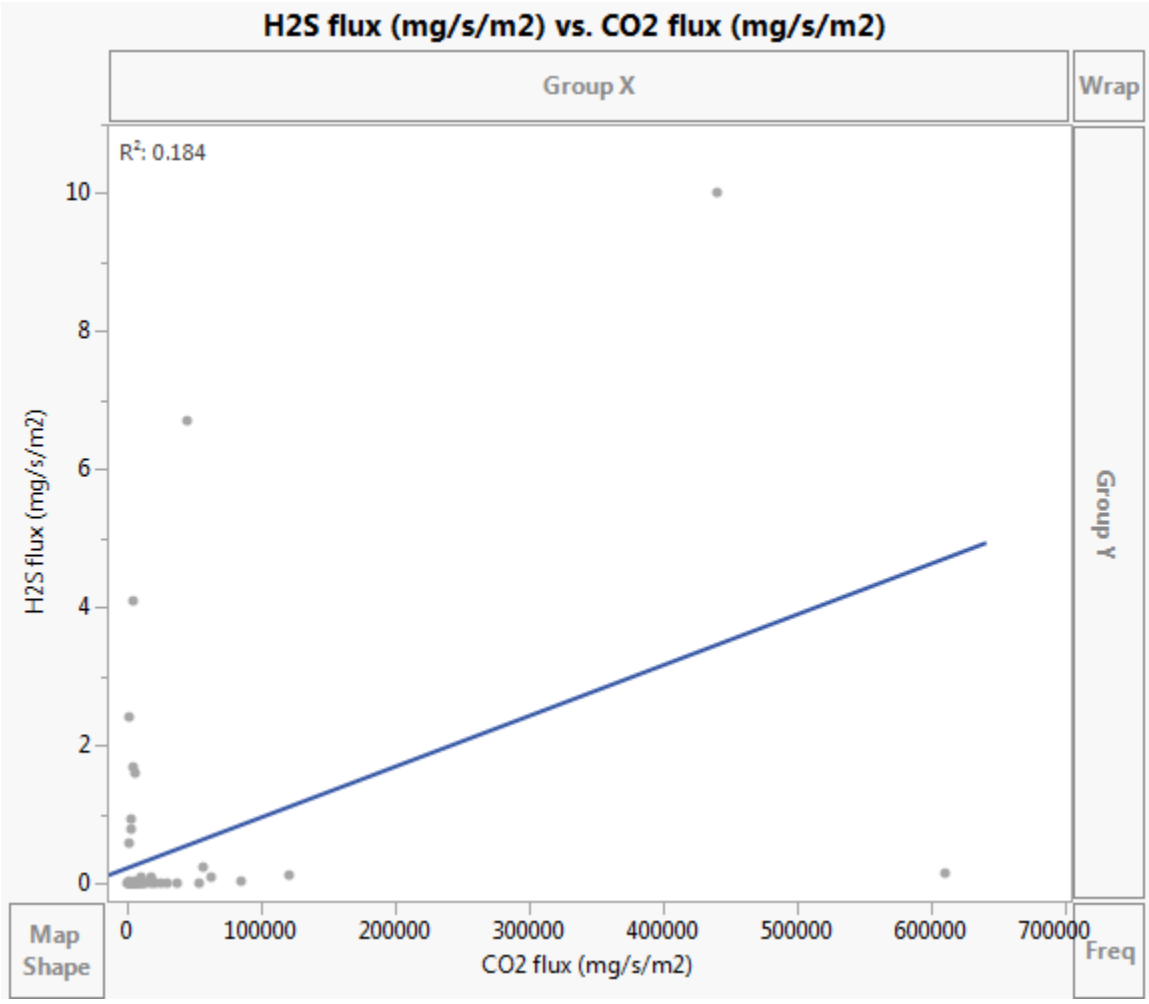

CH4 flux (mg/s/m2) vs. H2S flux (mg/s/m2)
Group X
Wrap
R²: 0.016
3500
3000
2500
2000
1500
1000
500
0
CH4 flux (mg/s/m2)
Group Y
Map Shape
0
2
4
6
8
10
H2S flux (mg/s/m2)
Freq


Temp. (°C) vs. CO2 flux (mg/s/m2)
Group X
Wrap
R²: 0.266
100
80
60
40
20
0
Temp. (°C)
Group Y
Map Shape
0
100000
200000
300000
400000
500000
600000
700000
CO2 flux (mg/s/m2)
Freq


Temp. (°C) vs. H2S flux (mg/s/m2)
Group X
Wrap
R²: 0.052
100
80
60
40
20
0
Temp. (°C)
Group Y
Map Shape
0
2
4
6
8
10
H2S flux (mg/s/m2)
Freq


CH4 flux (mg/s/m2) vs. CO2 flux (mg/s/m2)
Group X
Wrap
R²: 0.188
3500
3000
2500
2000
1500
1000
500
0
CH4 flux (mg/s/m2)
Group Y
Map Shape
0
100000
200000
300000
400000
500000
600000
700000
CO2 flux (mg/s/m2)
Freq


Temp. (°C) vs. CH4 flux (mg/s/m2)
Group X
Wrap
R²: 0.226
100
80
60
40
20
0
Temp. (°C)
Group Y
Map Shape
0
500
1000
1500
2000
2500
3000
3500
CH4 flux (mg/s/m2)
Freq


H2S flux (mg/s/m2) vs. CO2 flux (mg/s/m2)
Group X
Wrap
R²: 0.184
10
8
6
4
2
0
H2S flux (mg/s/m2)
Group Y
Map Shape
0
100000
200000
300000
400000
500000
600000
700000
CO2 flux (mg/s/m2)
Freq

Appendix IV: USDA Soil Data Reports for Lotts Creek and Truman Shepherd.

Custom Soil Resource Report for the Lotts Creek Coal Fire, Perry County, Kentucky; and the Truman Shepherd Coal Fire in Knott and Floyd Counties, Kentucky

October 29, 2014

Soil surveys contain information that affects land-use planning in survey areas. They highlight soil limitations that affect various land uses and provide information about the properties of the soils in the survey areas. Soil surveys are designed for many different users, including farmers, ranchers, foresters, agronomists, urban planners, community officials, engineers, developers, builders, and home buyers. Also, conservationists, teachers, students, and specialists in recreation, waste disposal, and pollution control can use the surveys to help them understand, protect, or enhance the environment.

Various land-use regulations of Federal, State, and local governments may impose special restrictions on land use or land treatment. Soil surveys identify soil properties that are used in making various land-use or land treatment decisions. The information is intended to help land users identify and reduce the effects of soil limitations on various land uses. The landowner or user is responsible for identifying and complying with existing laws and regulations.

Although soil survey information can be used for general farm, local, and wider area planning, onsite investigation is needed to supplement this information in some cases. Examples include soil-quality assessments http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/ and certain conservation and engineering applications. For more detailed information, contact your local USDA Service Center (http://offices.sc.egov.usda.gov/locator/app?agency=nrcs) or your NRCS State Soil Scientist (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/contactus/?cid=nrcs142p2_053951).

Great differences in soil properties can occur within short distances. Some soils are seasonally wet or subject to flooding. Some are too unstable to be used as a foundation for buildings or roads. Clayey or wet soils are poorly suited to use as septic tank absorption fields. Also, a high water table makes a soil poorly suited to basements or underground installations.

The National Cooperative Soil Survey is a joint effort of the United States Department of Agriculture and other Federal agencies, State agencies including the Agricultural Experiment Stations, and local agencies. The Natural Resources Conservation Service (NRCS) has leadership for the Federal part of the National Cooperative Soil Survey.

Information about soils is updated periodically. Updated information is available through the NRCS Web Soil Survey, the site for official soil survey information.

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Soil surveys are made to provide information about the soils and miscellaneous areas in a specific area. They include a description of the soils and miscellaneous areas and their location on the landscape and tables that show soil properties and limitations affecting various uses. Soil scientists observed the steepness, length, and shape of the slopes; the general pattern of drainage; the kinds of crops and native plants; and the kinds of bedrock. They observed and described many soil profiles. A soil profile is the sequence of natural layers, or horizons, in a soil. The profile extends from the surface

down into the unconsolidated material in which the soil formed or from the surface down to bedrock. The unconsolidated material is devoid of roots and other living organisms and has not been changed by other biological activity.

Currently, soils are mapped according to the boundaries of major land resource areas (MLRAs). MLRAs are geographically associated land resource units that share common characteristics related to physiography, geology, climate, water resources, soils, biological resources, and land uses (USDA, 2006). Soil survey areas typically consist of parts of one or more MLRA.

The soils and miscellaneous areas in a survey area occur in an orderly pattern that is related to the geology, landforms, relief, climate, and natural vegetation of the area. Each kind of soil and miscellaneous area is associated with a particular kind of landform or with a segment of the landform. By observing the soils and miscellaneous areas in the survey area and relating their position to specific segments of the landform, a soil scientist develops a concept, or model, of how they were formed. Thus, during mapping, this model enables the soil scientist to predict with a considerable degree of accuracy the kind of soil or miscellaneous area at a specific location on the landscape.

Commonly, individual soils on the landscape merge into one another as their characteristics gradually change. To construct an accurate soil map, however, soil scientists must determine the boundaries between the soils. They can observe only a limited number of soil profiles. Nevertheless, these observations, supplemented by an understanding of the soil-vegetation-landscape relationship, are sufficient to verify predictions of the kinds of soil in an area and to determine the boundaries.

Soil scientists recorded the characteristics of the soil profiles that they studied. They noted soil color, texture, size and shape of soil aggregates, kind and amount of rock fragments, distribution of plant roots, reaction, and other features that enable them to identify soils. After describing the soils in the survey area and determining their

properties, the soil scientists assigned the soils to taxonomic classes (units). Taxonomic classes are concepts. Each taxonomic class has a set of soil characteristics with precisely defined limits. The classes are used as a basis for comparison to classify soils systematically. Soil taxonomy, the system of taxonomic classification used in the United States, is based mainly on the kind and character of soil properties and the arrangement of horizons within the profile. After the soil scientists classified and named the soils in the survey area, they compared the individual soils with similar soils in the same taxonomic class in other areas so that they could confirm data and assemble additional data based on experience and research.

The objective of soil mapping is not to delineate pure map unit components; the objective is to separate the landscape into landforms or landform segments that have similar use and management requirements. Each map unit is defined by a unique combination of soil components and/or miscellaneous areas in predictable proportions. Some components may be highly contrasting to the other components of the map unit. The presence of minor components in a map unit in no way diminishes the usefulness or accuracy of the data. The delineation of such landforms and landform segments on the map provides sufficient information for the development of resource plans. If intensive use of small areas is planned, onsite investigation is needed to define and locate the soils and miscellaneous areas.

Soil scientists make many field observations in the process of producing a soil map. The frequency of observation is dependent upon several factors, including scale of mapping, intensity of mapping, design of map units, complexity of the landscape, and experience of the soil scientist. Observations are made to test and refine the soil-landscape model and predictions and to verify the classification of the soils at specific locations. Once the soil-landscape model is refined, a significantly smaller number of measurements of individual soil properties are made and recorded. These measurements may include field measurements, such as those for color, depth to bedrock, and texture, and laboratory measurements, such as those for content of sand, silt, clay, salt, and other components. Properties of each soil typically vary from one

point to another across the landscape.

Observations for map unit components are aggregated to develop ranges of characteristics for the components. The aggregated values are presented. Direct measurements do not exist for every property presented for every map unit component. Values for some properties are estimated from combinations of other properties.

While a soil survey is in progress, samples of some of the soils in the area generally are collected for laboratory analyses and for engineering tests. Soil scientists interpret the data from these analyses and tests as well as the field-observed characteristics and the soil properties to determine the expected behavior of the soils under different uses. Interpretations for all of the soils are field tested through observation of the soils in different uses and under different levels of management. Some interpretations are modified to fit local conditions, and some new interpretations are developed to meet local needs. Data are assembled from other sources, such as research information, production records, and field experience of specialists. For example, data on crop yields under defined levels of management are assembled from farm records and from field or plot experiments on the same kinds of soil.

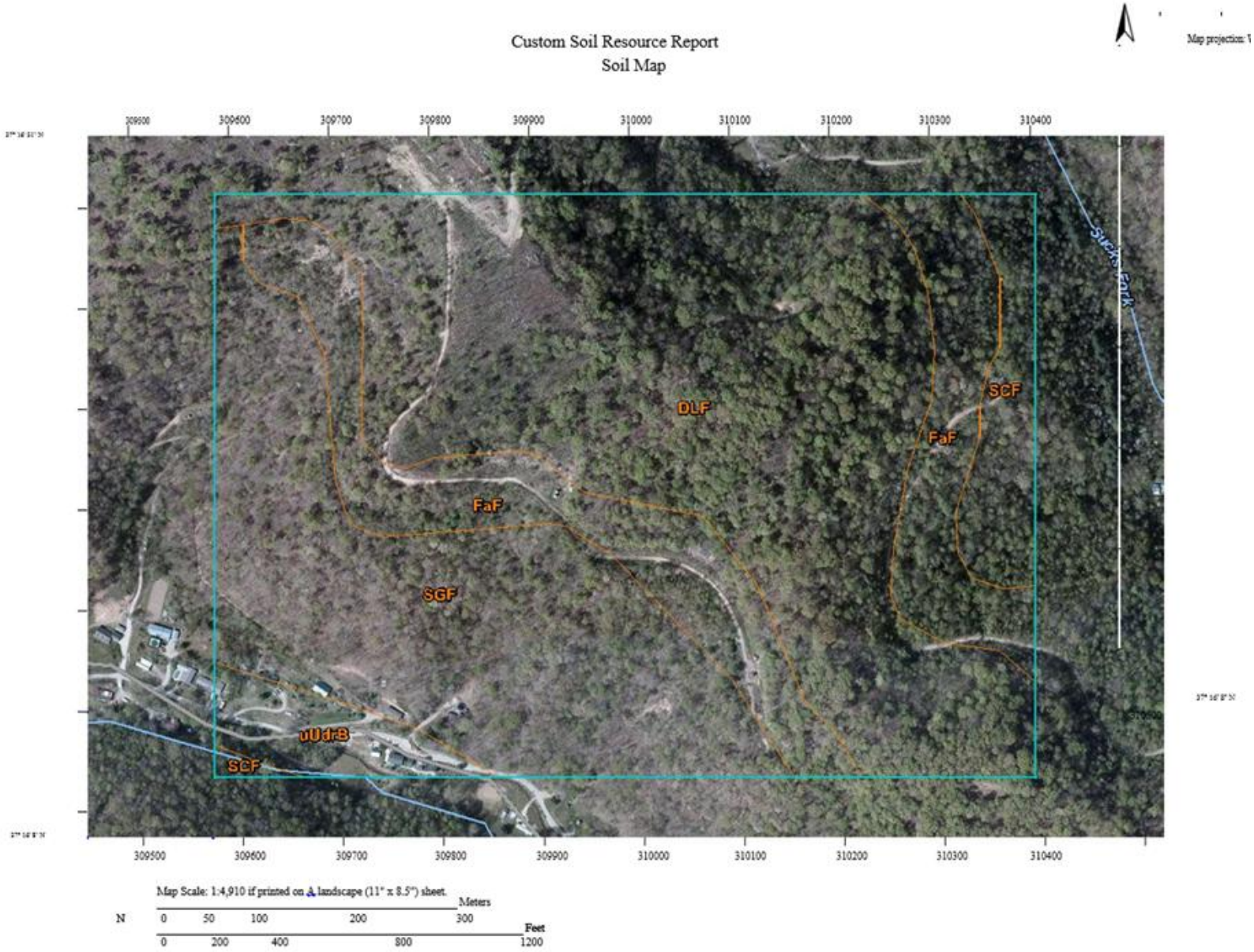
Predictions about soil behavior are based not only on soil properties but also on such variables as climate and biological activity. Soil conditions are predictable over long periods of time, but they are not predictable from year to year. For example, soil scientists can predict with a fairly high degree of accuracy that a given soil will have a high water table within certain depths in most years, but they cannot predict that a high water table will always be at a specific level in the soil on a specific date.

After soil scientists located and identified the significant natural bodies of soil in the survey area, they drew the boundaries of these bodies on aerial photographs and identified each as a specific map unit. Aerial photographs show trees, buildings, fields, roads, and rivers, all of which help in locating boundaries accurately.

Soil Map

The soil map section includes the soil map for the defined area of interest, a list of soil map units on the map and extent of each map unit, and cartographic symbols displayed on the map. Also presented are various metadata about data used to produce the map, and a description of each soil map unit.

Custom Soil Resource Report
Soil Map



MAP LEGEND

MAP INFORMATION

The soil surveys that comprise your AOI were mapped at 1:24,000.

Warning: Soil Map may not be valid at this scale.

Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Leslie and Perry Counties, Kentucky
Survey Area Data: Version 11, Sep 17, 2014

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: Apr 18, 2010—Oct 6, 2011

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

Map Unit Legend

Leslie and Perry Counties, Kentucky (KY633)			
Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
DLF	Matewan-Marrowbone-Latham complex, 20 to 80 percent slopes, very rocky	53.5	45.5%
FaF	Fairpoint and Bethesda soils, 2 to 70 percent slopes, benched, stony	22.1	18.8%
SCF	Shelocta-Cutshin-Gilpin complex, 20 to 75 percent slopes, very stony	5.7	4.9%
SGF	Shelocta-Highsplint-Gilpin complex, 20 to 75 percent slopes, very stony	32.0	27.2%
uUdrB	Udorthents-Urban land-Grigsby complex, 0 to 6 percent slopes, occasionally flooded	4.3	3.6%
Totals for Area of Interest		**117.6**	**100.0%**

Map Unit Descriptions

The map units delineated on the detailed soil maps in a soil survey represent the soils or miscellaneous areas in the survey area. The map unit descriptions, along with the maps, can be used to determine the composition and properties of a unit.

A map unit delineation on a soil map represents an area dominated by one or more major kinds of soil or miscellaneous areas. A map unit is identified and named according to the taxonomic classification of the dominant soils. Within a taxonomic class there are precisely defined limits for the properties of the soils. On the landscape, however, the soils are natural phenomena, and they have the characteristic variability of all natural phenomena. Thus, the range of some observed properties may extend beyond the limits defined for a taxonomic class. Areas of soils of a single taxonomic class rarely, if ever, can be mapped without including areas of other taxonomic classes. Consequently, every map

unit is made up of the soils or miscellaneous areas for which it is named and some minor components that belong to taxonomic classes other than those of the major soils.

Most minor soils have properties similar to those of the dominant soil or soils in the map unit, and thus they do not affect use and management. These are called noncontrasting, or similar, components. They may or may not be mentioned in a particular map unit description. Other minor components, however, have properties and behavioral characteristics divergent enough to affect use or to require different management. These are called contrasting, or dissimilar, components. They generally are in small areas and could not be mapped separately because of the scale used. Some small areas of strongly contrasting soils or miscellaneous areas are identified by a special symbol on the maps. If included in the database for a given area, the contrasting minor components are identified in the map unit descriptions along with some characteristics of each. A few areas of minor components may not have been observed, and consequently they are not mentioned in the descriptions, especially where the pattern was so complex that it was impractical to make enough observations to identify all the soils and miscellaneous areas on the landscape.

The presence of minor components in a map unit in no way diminishes the usefulness or accuracy of the data. The objective of mapping is not to delineate pure taxonomic classes but rather to separate the landscape into landforms or landform segments that have similar use and management requirements. The delineation of such segments on the map provides sufficient information for the development of resource plans. If intensive use of small areas is planned, however, onsite investigation is needed to define and locate the soils and miscellaneous areas.

An identifying symbol precedes the map unit name in the map unit descriptions. Each description includes general facts about the unit and gives important soil properties and qualities.Soils with similar profiles make up a *soil series*. Except for differences in texture of the surface layer, all the soils of a series have major horizons that are similar in composition, thickness, and arrangement.

Soils of one series can differ in texture of the surface layer, slope, stoniness, salinity, degree of erosion, and other characteristics that affect their use. On the basis of such differences, a soil series is divided into *soil phases*. Most of the areas shown on the detailed soil maps are phases of soil series. The name of a soil phase commonly indicates a feature that affects use or management. For example, Alpha silt loam, 0 to 2 percent slopes, is a phase of the Alpha series.

Some map units are made up of two or more major soils or miscellaneous areas. These map units are complexes, associations, or undifferentiated groups.

A *complex* consists of two or more soils or miscellaneous areas in such an intricate pattern or in such small areas that they cannot be shown separately on the maps. The pattern and proportion of the soils or miscellaneous areas are somewhat similar in all areas. Alpha-Beta complex, 0 to 6 percent slopes, is an example.

An *association* is made up of two or more geographically associated soils or miscellaneous areas that are shown as one unit on the maps. Because of present or anticipated uses of the map units in the survey area, it was not considered practical or necessary to map the soils or miscellaneous areas separately. The pattern and relative proportion of the soils or miscellaneous areas are somewhat similar. Alpha-Beta association, 0 to 2 percent slopes, is an example.

An *undifferentiated group* is made up of two or more soils or miscellaneous areas that could be mapped individually but are mapped as one unit because similar interpretations can be made for use and management. The pattern and proportion of the soils or miscellaneous areas in a mapped area are not uniform. An area can be made up of only one of the major soils or miscellaneous areas, or it can be made up of all of them. Alpha and Beta soils, 0 to 2 percent slopes, is an example. Some surveys include *miscellaneous areas*. Such areas have little or no soil material and support little or no vegetation. A rock outcrop is an example.

Leslie and Perry Counties, Kentucky

DLF—Matewan-Marrowbone-Latham complex, 20 to 80 percent slopes, very rocky

Map Unit Setting
National map unit symbol: 2tqh8
Elevation: 700 to 2,400 feet
Mean annual precipitation: 37 to 54 inches
Mean annual air temperature: 42 to 68 degrees F
Frost-free period: 155 to 220 days
Farmland classification: Not prime farmland

Map Unit Composition
Matewan, very stony, and similar soils: 30 percent *Marrowbone, very stony, and similar soils:* 25 percent *Latham, very stony, and similar soils:* 15 percent *Minor components:* 30 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Matewan, Very Stony

Setting
Landform: Ridges
Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex
Across-slope shape: Linear
Parent material: Loamy-skeletal residuum weathered from sandstone

Typical profile
Oi - 0 to 1 inches: channery slightly decomposed plant material *A - 1 to 3 inches:* channery fine sandy loam
BA - 3 to 7 inches: channery fine sandy loam
Bw1 - 7 to 21 inches: very channery fine sandy loam
Bw2 - 21 to 28 inches: extremely channery fine sandy loam
R - 28 to 37 inches: bedrock

Properties and qualities
Slope: 20 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 24 to 40 inches to lithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low (0.00 to 0.01 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* None
Frequency of ponding: None
Calcium carbonate, maximum in profile: 1 percent *Sodium adsorption ratio, maximum in profile:* 1.0
Available water storage in profile: Very low (about 2.3 inches)

Interpretive groups
Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e
Hydrologic Soil Group: A

Description of Marrowbone, Very Stony

Setting
Landform: Ridges
Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex
Across-slope shape: Linear

Parent material: Coarse-loamy residuum weathered from sandstone

Typical profile

Oi - 0 to 1 inches: slightly decomposed plant material
A - 1 to 5 inches: fine sandy loam *Bw1 - 5 to 10 inches:* loam
Bw2 - 10 to 17 inches: fine sandy loam *Bw3 - 17 to 23 inches:* loam
BC - 23 to 28 inches: channery loam *R - 28 to 38 inches:* bedrock

Properties and qualities

Slope: 20 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 24 to 32 inches to lithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low (0.00 to 0.01 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* None
Frequency of ponding: None
Available water storage in profile: Low (about 3.6 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil Group:* B

Description of Latham, Very Stony

Setting

Landform: Ridges
Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex
Across-slope shape: Concave
Parent material: Clayey residuum weathered from shale and siltstone

Typical profile

Oi - 0 to 1 inches: channery slightly decomposed plant material
A - 1 to 2 inches: silt loam
BA - 2 to 6 inches: silty clay loam *Bt - 6 to 20 inches:* silty clay
BC - 20 to 25 inches: silty clay loam *Cr - 25 to 36 inches:* bedrock
R - 36 to 46 inches: bedrock

Properties and qualities

Slope: 20 to 80 percent

Percent of area covered with surface fragments: 1.0 percent

Depth to restrictive feature: 24 to 34 inches to paralithic bedrock; 34 to 45 inches to lithic bedrock

Natural drainage class: Moderately well drained

Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low (0.00 to 0.01 in/hr)

Depth to water table: About 6 to 24 inches *Frequency of flooding:* None

Frequency of ponding: None

Available water storage in profile: Very low (about 2.7 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil Group:* C/D

Minor Components

Gilpin, very stony

Percent of map unit: 10 percent *Landform:* Ridges

Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex

Across-slope shape: Linear

Shelocta, very stony

Percent of map unit: 7 percent *Landform:* Ridges

Landform position (two-dimensional): Shoulder

Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Concave, convex

Across-slope shape: Linear

Rock outcrop

Percent of map unit: 5 percent

Fedscreek, very stony

Percent of map unit: 5 percent *Landform:* Ridges

Landform position (two-dimensional): Shoulder

Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Convex

Across-slope shape: Linear

Ramsey, very stony

Percent of map unit: 3 percent *Landform:* Ridges

Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex

Across-slope shape: Convex

FaF—Fairpoint and Bethesda soils, 2 to 70 percent slopes, benched, stony

Map Unit Setting

National map unit symbol: 2tqhd
Elevation: 720 to 1,510 feet
Mean annual precipitation: 45 to 57 inches
Mean annual air temperature: 43 to 68 degrees F
Frost-free period: 169 to 203 days
Farmland classification: Not prime farmland

Map Unit Composition

Fairpoint, unstable fill, and similar soils: 55 percent *Bethesda, unstable fill, and similar soils:* 30 percent *Minor components:* 15 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Fairpoint, Unstable Fill

Setting

Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank *Down-slope shape:* Linear
Across-slope shape: Linear
Parent material: Loamy-skeletal coal extraction mine spoil derived from sandstone and shale

Typical profile

Ap - 0 to 11 inches: channery loam
C1 - 11 to 32 inches: very channery loam
C2 - 32 to 41 inches: extremely channery loam
C3 - 41 to 51 inches: extremely flaggy loam *C4 - 51 to 58 inches:* extremely flaggy silt loam *C5 - 58 to 72 inches:* extremely flaggy loam

Properties and qualities

Slope: 2 to 70 percent
Percent of area covered with surface fragments: 0.0 percent *Depth to restrictive feature:* More than 80 inches
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately high (0.20 to 0.57 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* None
Frequency of ponding: None
Available water storage in profile: Low (about 5.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7s
Hydrologic Soil Group: C

Description of Bethesda, Unstable Fill

Setting

Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank *Down-slope shape:* Linear
Across-slope shape: Linear
Parent material: Loamy-skeletal coal extraction mine spoil derived from sandstone and shale

Typical profile

Ap - 0 to 12 inches: channery silt loam
C1 - 12 to 36 inches: very channery loam
C2 - 36 to 58 inches: very channery loam
C3 - 58 to 72 inches: very channery loam

Properties and qualities

Slope: 2 to 70 percent
Percent of area covered with surface fragments: 0.0 percent *Depth to restrictive feature:* More than 80 inches
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately high (0.20 to 0.57 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* None
Frequency of ponding: None
Available water storage in profile: Low (about 5.4 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7s *Hydrologic Soil Group:* C

Minor Components

Udorthents, unstable fill

Percent of map unit: 5 percent
Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank
Down-slope shape: Linear
Across-slope shape: Linear

Shelocta, very stony

Percent of map unit: 3 percent
Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank
Down-slope shape: Concave
Across-slope shape: Linear

Matewan, very stony

Percent of map unit: 3 percent
Landform: Ridges
Landform position (three-dimensional): Mountaintop
Down-slope shape: Convex
Across-slope shape: Linear

Urban land

Percent of map unit: 2 percent
Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank
Down-slope shape: Linear
Across-slope shape: Linear

Dumps, mine (tailings & tipples)

Percent of map unit: 2 percent
Landform: Ridges
Landform position (three-dimensional): Mountaintop
Down-slope shape: Linear
Across-slope shape: Linear, convex

SCF—Shelocta-Cutshin-Gilpin complex, 20 to 75 percent slopes, very stony

Map Unit Setting

National map unit symbol: 2tqhb
Elevation: 680 to 2,400 feet
Mean annual precipitation: 40 to 54 inches
Mean annual air temperature: 42 to 69 degrees F
Frost-free period: 147 to 196 days
Farmland classification: Not prime farmland

Map Unit Composition

Shelocta, very stony, and similar soils: 35 percent *Cutshin, very stony, and similar soils:* 25 percent *Gilpin, very stony, and similar soils:* 15 percent *Minor components:* 25 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Shelocta, Very Stony

Setting

Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank *Down-slope shape:* Concave
Across-slope shape: Linear
Parent material: Fine-loamy colluvium derived from sandstone and shale over clayey residuum weathered from shale and siltstone

Typical profile

Oi - 0 to 1 inches: slightly decomposed plant material
A - 1 to 3 inches: silt loam
BA - 3 to 7 inches: loam
Bt1 - 7 to 23 inches: channery silt loam *2Bt2 - 23 to 34 inches:* channery silt loam
2Bt3 - 34 to 45 inches: very channery silt loam *2C - 45 to 59 inches:* very parachannery silt loam
2Cr - 59 to 69 inches: bedrock

Properties and qualities

Slope: 20 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 48 to 65 inches to paralithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low (0.00 to 0.00 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* None
Frequency of ponding: None
Available water storage in profile: Moderate (about 7.3 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil Group:* B

Description of Cutshin, Very Stony

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Lower third of mountainflank *Down-slope shape:* Concave
Across-slope shape: Concave
Parent material: Fine-loamy colluvium derived from sandstone and shale

Typical profile

Oi - 0 to 2 inches: very channery slightly decomposed plant material *A - 2 to 10 inches:* very channery loam

AB - 10 to 19 inches: channery loam *Bw1 - 19 to 30 inches:* channery loam *Bw2 - 30 to 50 inches:* channery loam *Cr - 50 to 60 inches:* bedrock

Properties and qualities

Slope: 20 to 80 percent

Percent of area covered with surface fragments: 1.0 percent

Depth to restrictive feature: 40 to 60 inches to paralithic bedrock

Natural drainage class: Well drained

Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately high (0.00 to 0.20 in/hr)

Depth to water table: More than 80 inches *Frequency of flooding:* None

Frequency of ponding: None

Sodium adsorption ratio, maximum in profile: 1.0 *Available water storage in profile:* Low (about 5.5 inches)

Interpretive groups

Land capability classification (irrigated): None specified

Land capability classification (nonirrigated): 7e

Hydrologic Soil Group: A

Description of Gilpin, Very Stony

Setting

Landform: Mountain slopes

Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Convex

Across-slope shape: Linear

Parent material: Fine-loamy residuum weathered from sandstone and shale

Typical profile

Oi - 0 to 1 inches: channery slightly decomposed plant material *A - 1 to 5 inches:* channery silt loam

Bt1 - 5 to 11 inches: channery silt loam *Bt2 - 11 to 20 inches:* channery silt loam *Bt3 - 20 to 28 inches:* channery loam

R - 28 to 38 inches: bedrock

Properties and qualities

Slope: 20 to 80 percent

Percent of area covered with surface fragments: 1.0 percent

Depth to restrictive feature: 24 to 40 inches to lithic bedrock

Natural drainage class: Well drained

Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low (0.00 to 0.01 in/hr)

Depth to water table: More than 80 inches *Frequency of flooding:* None

Frequency of ponding: None

Available water storage in profile: Very low (about 3.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil Group:* C

Minor Components

Cloverlick, very stony

Percent of map unit: 8 percent
Landform: Mountain slopes
Landform position (three-dimensional): Center third of mountainflank *Down-slope shape:* Concave
Across-slope shape: Concave

Marrowbone, very stony

Percent of map unit: 7 percent
Landform: Mountain slopes
Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Convex
Across-slope shape: Convex

Highsplint, very stony

Percent of map unit: 5 percent
Landform: Mountain slopes
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Lower third of mountainflank
Down-slope shape: Concave *Across-slope shape:* Linear

Sequoia, very stony

Percent of map unit: 3 percent
Landform: Mountain slopes
Landform position (two-dimensional): Summit
Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Convex
Across-slope shape: Convex

Rock outcrop

Percent of map unit: 2 percent

SGF—Shelocta-Highsplint-Gilpin complex, 20 to 75 percent slopes, very stony

Map Unit Setting

National map unit symbol: 2qytm
Elevation: 680 to 2,460 feet
Mean annual precipitation: 28 to 58 inches
Mean annual air temperature: 42 to 68 degrees F
Frost-free period: 147 to 200 days
Farmland classification: Not prime farmland

Map Unit Composition

Shelocta, very stony, and similar soils: 55 percent *Highsplint, very stony, and similar soils:* 20 percent *Gilpin, very stony, and similar soils:* 15 percent *Minor components:* 10 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Shelocta, Very Stony

Setting

Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank *Down-slope shape:* Concave
Across-slope shape: Linear

Parent material: Fine-loamy colluvium derived from sandstone and shale

Typical profile

Oi - 0 to 1 inches: slightly decomposed plant material
A - 1 to 3 inches: silt loam *BA - 3 to 7 inches:* loam
Bt1 - 7 to 23 inches: channery silt loam *2Bt2 - 23 to 34 inches:* channery silt loam
2Bt3 - 34 to 45 inches: very channery silt loam
2C - 45 to 59 inches: very parachannery silt loam
2Cr - 59 to 69 inches: bedrock

Properties and qualities

Slope: 20 to 75 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 48 to 65 inches to paralithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low (0.00 to 0.00 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* None
Frequency of ponding: None
Available water storage in profile: Moderate (about 7.3 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil Group:* B

Description of Highsplint, Very Stony

Setting

Landform: Hillslopes
Landform position (two-dimensional): Footslope *Landform position (three-dimensional):* Side slope *Down-slope shape:* Concave
Across-slope shape: Linear
Parent material: Loamy-skeletal fine-loamy colluvium derived from sandstone and shale

Typical profile

Oi - 0 to 1 inches: very channery slightly decomposed plant material *A - 1 to 4 inches:* very channery silt loam
BA - 4 to 11 inches: very channery silt loam *Bw1 - 11 to 28 inches:* very channery clay loam
Bw2 - 28 to 48 inches: very channery loam *BC - 48 to 85 inches:* very channery loam

Properties and qualities

Slope: 20 to 75 percent
Percent of area covered with surface fragments: 1.0 percent *Depth to restrictive feature:* More than 80 inches
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.20 to 2.00 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* None
Frequency of ponding: None
Available water storage in profile: Low (about 5.7 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil*

Group: A

Description of Gilpin, Very Stony

Setting

Landform: Mountain slopes
Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Convex
Across-slope shape: Linear
Parent material: Fine-loamy residuum weathered from sandstone and shale

Typical profile

Oi - 0 to 1 inches: channery slightly decomposed plant material *A - 1 to 5 inches:* channery silt loam
Bt1 - 5 to 11 inches: channery silt loam *Bt2 - 11 to 20 inches:* channery silt loam *Bt3 - 20 to 28 inches:* channery loam
R - 28 to 38 inches: bedrock

Properties and qualities

Slope: 20 to 75 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 24 to 40 inches to lithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low (0.00 to 0.01 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* None
Frequency of ponding: None
Available water storage in profile: Very low (about 3.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil Group:* C

Minor Components

Ramsey, very stony

Percent of map unit: 5 percent
Landform: Hillslopes
Landform position (two-dimensional): Shoulder *Landform position (three-dimensional):* Nose slope *Down-slope shape:* Convex
Across-slope shape: Convex

Marrowbone, very stony

Percent of map unit: 3 percent
Landform: Mountain slopes
Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Convex
Across-slope shape: Convex

Rock outcrop

Percent of map unit: 2 percent

uUdrB—Udorthents-Urban land-Grigsby complex, 0 to 6 percent slopes, occasionally flooded

Map Unit Setting

National map unit symbol: 2mff7
Elevation: 700 to 1,400 feet
Mean annual precipitation: 28 to 54 inches
Mean annual air temperature: 42 to 68 degrees F
Frost-free period: 156 to 222 days
Farmland classification: Not prime farmland

Map Unit Composition

Udorthents, unstable fill, and similar soils: 40 percent *Urban land, occasionally flooded:* 35 percent
Grigsby, occasionally flooded, and similar soils: 15 percent *Minor components:* 10 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Udorthents, Unstable Fill

Setting

Landform: Flood plains
Landform position (two-dimensional): Toeslope *Down-slope shape:* Linear
Across-slope shape: Linear
Parent material: Loamy skeletal mine spoil or earthy fill derived from interbedded sedimentary rock

Typical profile

Ap - 0 to 5 inches: very channery silt loam *C1 - 5 to 22 inches:* very channery silt loam *C2 - 22 to 35 inches:* very channery silt loam
C3 - 35 to 52 inches: channery loam
C4 - 52 to 64 inches: channery loam
2C5 - 64 to 80 inches: extremely gravelly loamy sand

Properties and qualities

Slope: 0 to 6 percent
Depth to restrictive feature: More than 80 inches *Natural drainage class:* Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately high (0.20 to 0.57 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* Occasional *Frequency of ponding:* None
Available water storage in profile: Low (about 4.7 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 6s
Hydrologic Soil Group: C

Description of Urban Land, Occasionally Flooded

Setting

Landform: Flood plains

Properties and qualities

Slope: 0 to 6 percent
Frequency of flooding: Occasional

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8

Description of Grigsby, Occasionally Flooded

Setting

Landform: Flood plains
Landform position (two-dimensional): Toeslope *Down-slope shape:* Linear
Across-slope shape: Linear
Parent material: Coarse-loamy alluvium derived from sedimentary rock

Typical profile

Ap - 0 to 6 inches: loam *Bw1 - 6 to 14 inches:* loam
Bw2 - 14 to 30 inches: sandy loam
C1 - 30 to 45 inches: stratified loam to sand *C2 - 45 to 62 inches:* stratified sand to loam
C3 - 62 to 80 inches: stratified gravelly sand to loamy sand

Properties and qualities

Slope: 0 to 4 percent
Depth to restrictive feature: More than 80 inches *Natural drainage class:* Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.57 to 5.95 in/hr)
Depth to water table: About 42 to 80 inches *Frequency of flooding:* Occasional *Frequency of ponding:* None
Available water storage in profile: Moderate (about 7.5 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 2e *Hydrologic Soil Group:* A

Minor Components

Rowdy, occasionally flooded

Percent of map unit: 5 percent
Landform: Stream terraces
Landform position (two-dimensional): Toeslope
Landform position (three-dimensional): Tread
Down-slope shape: Convex *Across-slope shape:* Linear

Yeager, frequently flooded

Percent of map unit: 5 percent
Landform: Flood plains
Landform position (two-dimensional): Toeslope *Down-slope shape:* Linear
Across-slope shape: Linear

Custom Soil Resource Report for
The Truman Shepherd Fire, Knott and Floyd Counties, Kentucky

Custom Soil Resource Report
Soil Map

MAP LEGEND INFORMATION

Area of Interest (AOI)

Area of Interest (AOI)

Soils

Soil Map Unit Polygons

Soil Map Unit Lines

Soil Map Unit Points

Special Point Features

Blowout

Borrow Pit

Clay Spot

Closed Depression

Gravel Pit

Gravelly Spot

Landfill

Lava Flow

Marsh or swamp

Mine or Quarry

Miscellaneous Water

Perennial Water

Rock Outcrop

Saline Spot

Sandy Spot

Severely Eroded Spot

Sinkhole

Slide or Slip

Sodic Spot

Spoil Area

Stony Spot

Very Stony Spot

Wet Spot

Other

Special Line Features

Water Features

Streams and Canals

Transportation

Rails

Interstate Highways

US Routes

Major Roads

Local Roads

Background

Aerial Photography

MAP

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

The soil surveys that comprise your AOI were mapped at 1:24,000.

Warning: Soil Map may not be valid at this scale.

Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Floyd and Johnson Counties, Kentucky Survey Area Data: Version 10, Sep 17, 2014

Soil Survey Area: Knott and Letcher Counties, Kentucky Survey Area Data: Version 10, Sep 17, 2014

Your area of interest (AOI) includes more than one soil survey area. These survey areas may have been mapped at different scales, with a different land use in mind, at different times, or at different levels of detail. This may result in map unit symbols, soil properties, and interpretations that do not completely agree across soil survey area boundaries.

Map Unit Legend

Floyd and Johnson Counties, Kentucky (KY639)			
Map Unit Symbol	**Map Unit Name**	**Acres in AOI**	**Percent of AOI**
DgF	Matewan-Gilpin-Marrowbone complex, 20 to 80 percent slopes, very rocky	6.0	8.0%
HkF	Hazleton-Fedscreek-Kimper complex, 30 to 80 percent slopes, very stony	5.7	7.5%
HmF	Handshoe-Fedscreek-Marrowbone complex, 30 to 80 percent slopes, very stony	24.7	32.8%
SaF	Sharondale-Hazleton-Kimper complex, 30 to 80 percent slopes, extremely stony	9.4	12.5%
UrC	Udorthents-Urban land complex, 0 to 15 percent slopes	16.5	21.9%
Subtotals for Soil Survey Area		**62.3**	**82.6%**
Totals for Area of Interest		**75.4**	**100.0%**

Knott and Letcher Counties, Kentucky (KY626)			
Map Unit Symbol	**Map Unit Name**	**Acres in AOI**	**Percent of AOI**
CsF	Cloverlick-Shelocta-Kimper complex, 20 to 80 percent slopes, very stony	2.1	2.8%
FaF	Fedscreek-Shelocta-Handshoe complex, 30 to 80 percent slopes, very stony	0.8	1.0%
uUduE	Udorthents-Urban land-Rock outcrop complex, 0 to 35 percent slopes	10.2	13.5%
Subtotals for Soil Survey Area		**13.1**	**17.4%**
Totals for Area of Interest		**75.4**	**100.0%**

M

Floyd and Johnson Counties, Kentucky

DgF—Matewan-Gilpin-Marrowbone complex, 20 to 80 percent slopes, very rocky

Map Unit Setting

National map unit symbol: 2szxs
Elevation: 800 to 2,300 feet
Mean annual precipitation: 28 to 55 inches
Mean annual air temperature: 39 to 67 degrees F
Frost-free period: 140 to 210 days
Farmland classification: Not prime farmland

Map Unit Composition

Matewan, very stony, and similar soils: 30 percent *Gilpin, very stony, and similar soils:* 25 percent *Marrowbone, very stony, and similar soils:* 15 percent *Minor components:* 30 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Matewan, Very Stony

Setting

Landform: Ridges
Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex
Across-slope shape: Linear
Parent material: Loamy-skeletal residuum weathered from sandstone

Typical profile

Oi - 0 to 1 inches: channery slightly decomposed plant material *A - 1 to 3 inches:* channery fine sandy loam
BA - 3 to 7 inches: channery fine sandy loam
Bw1 - 7 to 21 inches: very channery fine sandy loam
Bw2 - 21 to 28 inches: extremely channery fine sandy loam
R - 28 to 37 inches: bedrock

Properties and qualities

Slope: 20 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 24 to 40 inches to lithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low (0.00 to 0.01 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Calcium carbonate, maximum in profile: 1 percent
Available water storage in profile: Very low (about 2.3 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* A

Description of Gilpin, Very Stony

Setting

Landform: Ridges
Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex
Across-slope shape: Linear
Parent material: Fine-loamy residuum weathered from sandstone and shale

Typical profile

Oi - 0 to 1 inches: channery slightly decomposed plant material *A - 1 to 5 inches:* channery silt loam
Bt1 - 5 to 11 inches: channery silt loam *Bt2 - 11 to 20 inches:* channery silt loam *Bt3 - 20 to 28 inches:* channery loam
R - 28 to 38 inches: bedrock

Properties and qualities

Slope: 20 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 24 to 40 inches to lithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low (0.00 to 0.01 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Very low (about 3.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* C

Description of Marrowbone, Very Stony

Setting

Landform: Ridges
Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex
Across-slope shape: Linear
Parent material: Coarse-loamy residuum weathered from sandstone

Typical profile

Oi - 0 to 1 inches: slightly decomposed plant material
A - 1 to 5 inches: fine sandy loam
Bw1 - 5 to 10 inches: loam
Bw2 - 10 to 17 inches: fine sandy loam
Bw3 - 17 to 23 inches: loam
BC - 23 to 28 inches: channery loam *R - 28 to 38 inches:* bedrock

Properties and qualities

Slope: 20 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 24 to 32 inches to lithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low

(0.00 to 0.01 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Low (about 3.6 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* B

Minor Components

Shelocta, very stony

Percent of map unit: 10 percent
Landform: Ridges
Landform position (two-dimensional): Shoulder
Landform position (three-dimensional): Upper third of mountainflank
Down-slope shape: Convex, concave
Across-slope shape: Linear

Fedscreek, very stony

Percent of map unit: 6 percent
Landform: Ridges
Landform position (two-dimensional): Shoulder
Landform position (three-dimensional): Upper third of mountainflank
Down-slope shape: Convex
Across-slope shape: Linear

Sequoia, very stony

Percent of map unit: 6 percent
Landform: Ridges
Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex
Across-slope shape: Concave

Latham, very stony

Percent of map unit: 3 percent
Landform: Ridges
Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex
Across-slope shape: Concave

Ramsey, very stony

Percent of map unit: 3 percent
Landform: Ridges
Landform position (two-dimensional): Summit *Landform position (three-dimensional):* Mountaintop *Down-slope shape:* Convex
Across-slope shape: Convex

Rock outcrop

Percent of map unit: 2 percent

HkF—Hazleton-Fedscreek-Kimper complex, 30 to 80 percent slopes, very stony

Map Unit Setting

National map unit symbol: lh6y
Elevation: 550 to 2,300 feet
Mean annual precipitation: 41 to 55 inches
Mean annual air temperature: 39 to 66 degrees F
Frost-free period: 128 to 186 days
Farmland classification: Not prime farmland

Map Unit Composition

Hazleton and similar soils: 30 percent
Kimper and similar soils: 25 percent
Fedscreek and similar soils: 25 percent
Minor components: 20 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Hazleton

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Loamy-skeletal colluvium derived from sedimentary rock

Typical profile

H1 - 0 to 5 inches: fine sandy loam
H2 - 5 to 38 inches: very channery sandy loam *H3 -*
38 to 62 inches: very flaggy fine sandy loam *R - 62 to*
72 inches: unweathered bedrock

Properties and qualities

Slope: 30 to 80 percent
Depth to restrictive feature: 40 to 72 inches to lithic bedrock
Natural drainage class: Well drained
Runoff class: Very high
Capacity of the most limiting layer to transmit water (Ksat): High (1.98 to 5.95 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Low (about 6.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e
Hydrologic Soil Group: A

Description of Kimper

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Loamy colluvium derived from sandstone and siltstone over

residuum

Typical profile

H1 - 0 to 6 inches: loam
H2 - 6 to 54 inches: very channery loam
H3 - 54 to 66 inches: very channery loam
R - 66 to 76 inches: unweathered bedrock

Properties and qualities

Slope: 30 to 80 percent
Depth to restrictive feature: 40 to 72 inches to lithic bedrock
Natural drainage class: Well drained
Runoff class: Very high
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.57 to 5.95 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: High (about 10.1 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* A

Description of Fedscreek

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Coarse-loamy colluvium derived from sedimentary rock

Typical profile

H1 - 0 to 5 inches: loam
H2 - 5 to 48 inches: channery loam
H3 - 48 to 63 inches: very channery fine sandy loam *R - 63 to 73 inches:* unweathered bedrock

Properties and qualities

Slope: 30 to 80 percent
Depth to restrictive feature: 40 to 72 inches to lithic bedrock
Natural drainage class: Well drained
Runoff class: Very high
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.57 to 5.95 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Moderate (about 8.5 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* A

Minor Components

Other soils

Percent of map unit: 5 percent

Dekalb

Percent of map unit: 5 percent

Gilpin

Percent of map unit: 5 percent

Marrowbone

Percent of map unit: 5 percent

HmF—Handshoe-Fedscreek-Marrowbone complex, 30 to 80 percent slopes, very stony

Map Unit Setting

National map unit symbol: 2tqhg
Elevation: 550 to 2,460 feet
Mean annual precipitation: 28 to 54 inches
Mean annual air temperature: 39 to 70 degrees F
Frost-free period: 140 to 222 days
Farmland classification: Not prime farmland

Map Unit Composition

Handshoe, very stony, and similar soils: 35 percent
Fedscreek, very stony, and similar soils: 25 percent
Marrowbone, very stony, and similar soils: 20 percent
Minor components: 20 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Handshoe, Very Stony

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Lower third of mountainflank
Down-slope shape: Concave
Across-slope shape: Linear
Parent material: Loamy-skeletal colluvium derived from sandstone and shale

Typical profile

Oi - 0 to 2 inches: very channery slightly decomposed plant material *A - 2 to 9 inches:* very channery loam
E - 9 to 16 inches: very channery loam
Bw1 - 16 to 34 inches: very channery sandy loam
Bw2 - 34 to 50 inches: very channery loam
Bw3 - 50 to 61 inches: channery loam
BC - 61 to 80 inches: very channery sandy loam

Properties and qualities

Slope: 30 to 80 percent
Percent of area covered with surface fragments: 1.0 percent *Depth to restrictive feature:* More than 80 inches
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.20 to 2.00 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Low (about 5.7 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* A

Description of Fedscreek, Very Stony

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Center third of mountainflank
Down-slope shape: Concave
Across-slope shape: Linear
Parent material: Coarse-loamy colluvium derived from sandstone and shale

Typical profile

Oi - 0 to 1 inches: channery slightly decomposed plant material
A - 1 to 4 inches: channery loam
BA - 4 to 8 inches: channery silt loam
Bw1 - 8 to 17 inches: channery loam *Bw2 - 17 to 30 inches:* channery loam *Bw3 - 30 to 39 inches:* channery loam *Bw4 - 39 to 48 inches:* channery loam *C1 - 48 to 60 inches:* very channery loam *C2 - 60 to 65 inches:* channery silt loam *R - 65 to 75 inches:* bedrock

Properties and qualities

Slope: 30 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 62 to 70 inches to lithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low (0.00 to 0.01 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Moderate (about 6.5 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* A

Description of Marrowbone, Very Stony

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Shoulder
Landform position (three-dimensional): Upper third of mountainflank
Down-slope shape: Convex
Across-slope shape: Convex
Parent material: Coarse-loamy residuum weathered from sandstone

Typical profile

Oi - 0 to 1 inches: slightly decomposed plant material
A - 1 to 5 inches: fine sandy loam
Bw1 - 5 to 10 inches: loam
Bw2 - 10 to 17 inches: fine sandy loam
Bw3 - 17 to 23 inches: loam

BC - 23 to 28 inches: channery loam *R -*
28 to 38 inches: bedrock

Properties and qualities

Slope: 30 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 24 to 32 inches to lithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low to moderately low (0.00 to 0.01 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Low (about 3.6 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* B

Minor Components

Shelocta, very stony

Percent of map unit: 8 percent
Landform: Mountain slopes
Landform position (two-dimensional): Footslope
Landform position (three-dimensional): Center third of mountainflank
Down-slope shape: Concave
Across-slope shape: Linear

Matewan, very stony

Percent of map unit: 6 percent
Landform: Mountain slopes
Landform position (two-dimensional): Summit
Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Convex
Across-slope shape: Linear

Gilpin, very stony

Percent of map unit: 3 percent
Landform: Mountain slopes
Landform position (two-dimensional): Shoulder
Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Convex
Across-slope shape: Linear

Ramsey, very stony

Percent of map unit: 2 percent
Landform: Mountain slopes
Landform position (two-dimensional): Summit
Landform position (three-dimensional): Upper third of mountainflank *Down-slope shape:* Convex
Across-slope shape: Convex

Rock outcrop

Percent of map unit: 1 percent

SaF—Sharondale-Hazleton-Kimper complex, 30 to 80 percent slopes, extremely

stony

Map Unit Setting

National map unit symbol: lh79
Elevation: 550 to 2,300 feet
Mean annual precipitation: 41 to 55 inches
Mean annual air temperature: 39 to 66 degrees F
Frost-free period: 128 to 186 days
Farmland classification: Not prime farmland

Map Unit Composition

Sharondale and similar soils: 35 percent
Hazleton and similar soils: 25 percent *Kimper and similar soils:* 15 percent *Minor components:* 25 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Sharondale

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Loamy-skeletal colluvium derived from sedimentary rock

Typical profile

H1 - 0 to 11 inches: channery loam
H2 - 11 to 32 inches: very channery loam
H3 - 32 to 78 inches: very channery loam

Properties and qualities

Slope: 30 to 80 percent
Depth to restrictive feature: More than 80 inches
Natural drainage class: Well drained
Runoff class: Very high
Capacity of the most limiting layer to transmit water (Ksat): High (1.98 to 5.95 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Moderate (about 8.8 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* A

Description of Hazleton

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Loamy-skeletal colluvium derived from sedimentary rock

Typical profile

H1 - 0 to 5 inches: fine sandy loam

H2 - 5 to 38 inches: very channery sandy loam *H3 - 38 to 62 inches:* very flaggy fine sandy loam *R - 62 to 72 inches:* unweathered bedrock

Properties and qualities

Slope: 30 to 80 percent
Depth to restrictive feature: 40 to 72 inches to lithic bedrock
Natural drainage class: Well drained
Runoff class: Very high
Capacity of the most limiting layer to transmit water (Ksat): High (1.98 to 5.95 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Low (about 6.0 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e
Hydrologic Soil Group: A

Description of Kimper

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Loamy colluvium derived from sandstone and siltstone over residuum

Typical profile

H1 - 0 to 6 inches: loam
H2 - 6 to 54 inches: very channery loam
H3 - 54 to 66 inches: very channery loam
R - 66 to 76 inches: unweathered bedrock

Properties and qualities

Slope: 30 to 80 percent
Depth to restrictive feature: 40 to 72 inches to lithic bedrock
Natural drainage class: Well drained
Runoff class: Very high
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.57 to 5.95 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: High (about 10.1 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* A

Minor Components

Dekalb

Percent of map unit: 5 percent

Fedscreek

Percent of map unit: 5 percent

Gilpin

Percent of map unit: 5 percent

Marrowbone

Percent of map unit: 5 percent

Shelocta

Percent of map unit: 5 percent

UrC—Udorthents-Urban land complex, 0 to 15 percent slopes

Map Unit Setting

National map unit symbol: lh7f
Elevation: 550 to 2,300 feet
Mean annual precipitation: 41 to 55 inches
Mean annual air temperature: 39 to 66 degrees F
Frost-free period: 128 to 186 days
Farmland classification: Not prime farmland

Map Unit Composition

Udorthents, unstable fill, and similar soils: 55 percent
Urban land: 20 percent
Minor components: 25 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Udorthents, Unstable Fill

Properties and qualities

Slope: 0 to 15 percent
Depth to restrictive feature: More than 80 inches
Runoff class: Medium
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 6s

Description of Urban Land

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8

Minor Components

Allegheny

Percent of map unit: 7 percent

Knowlton, rarely flooded

Percent of map unit: 6 percent

Landform: Stream terraces
Landform position (three-dimensional): Tread
Down-slope shape: Linear
Across-slope shape: Linear

Cotaco

Percent of map unit: 6 percent
Landform: Stream terraces

Nelse

Percent of map unit: 6 percent
Landform: Flood plains

Knott and Letcher Counties, Kentucky

CsF—Cloverlick-Shelocta-Kimper complex, 20 to 80 percent slopes, very stony

Map Unit Setting

National map unit symbol: 2qytk
Elevation: 700 to 2,000 feet
Mean annual precipitation: 28 to 52 inches
Mean annual air temperature: 39 to 68 degrees F
Frost-free period: 135 to 220 days
Farmland classification: Not prime farmland

Map Unit Composition

Cloverlick, very stony, and similar soils: 35 percent
Shelocta, very stony, and similar soils: 25 percent
Kimper, very stony, and similar soils: 20 percent *Minor components:* 20 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Cloverlick, Very Stony

Setting

Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank
Down-slope shape: Concave
Across-slope shape: Concave
Parent material: Skeletal loamy colluvium derived from sandstone and shale

Typical profile

Oi - 0 to 2 inches: channery slightly decomposed plant material
A - 2 to 8 inches: channery loam *Bw1 - 8 to 24 inches:* channery loam
Bw2 - 24 to 43 inches: very channery loam *BC - 43 to 80 inches:* very flaggy loam

Properties and qualities

Slope: 20 to 80 percent
Percent of area covered with surface fragments: 1.0 percent *Depth to restrictive feature:* More than 80 inches
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.60 to 6.00 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Sodium adsorption ratio, maximum in profile: 1.0
Available water storage in profile: Moderate (about 6.1 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e *Hydrologic Soil Group:* A

Description of Shelocta, Very Stony

Setting

Landform: Mountain slopes
Landform position (three-dimensional):
Mountainflank *Down-slope shape:* Concave
Across-slope shape: Linear
Parent material: Fine-loamy colluvium derived from sandstone and shale

Typical profile

Oi - 0 to 1 inches: slightly decomposed plant material
A - 1 to 3 inches: silt
loam *BA - 3 to 7*
inches: loam
Bt1 - 7 to 23 inches: channery silt loam
2Bt2 - 23 to 34 inches: channery silt
loam
2Bt3 - 34 to 45 inches: very channery silt loam
2C - 45 to 59 inches: very parachannery silt
loam
2Cr - 59 to 69 inches: bedrock

Properties and qualities

Slope: 20 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 48 to 65 inches to paralithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Very low (0.00 to 0.00
in/hr)
Depth to water table: More than 80
inches *Frequency of flooding:* None
Frequency of ponding: None
Available water storage in profile: Moderate (about 7.3 inches)

Interpretive groups

Land capability classification (irrigated): None
specified *Land capability classification*
(nonirrigated): 7e *Hydrologic Soil Group:* B

Description of Kimper, Very Stony

Setting

Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank
Down- slope shape: Concave
Across-slope shape: Linear
Parent material: Fine-loamy colluvium derived from sandstone and shale

Typical profile

Oi - 0 to 2 inches: very channery slightly decomposed plant material *A*
- 2 to 8 inches: very channery loam
BA - 8 to 13 inches: channery loam
Bw1 - 13 to 27 inches: channery
loam *Bw2 - 27 to 41 inches:*
channery loam
Bw3 - 41 to 52 inches: very channery loam

C1 - 52 to 64 inches: very channery fine sandy loam
C2 - 64 to 75 inches: very channery loam
R - 75 to 85 inches: bedrock

Properties and qualities

Slope: 20 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 65 to 80 inches to lithic bedrock
Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Sodium adsorption ratio, maximum in profile: 1.0
Available water storage in profile: Moderate (about 6.5 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7e
Hydrologic Soil Group: A

Minor Components

Fedscreek, very stony

Percent of map unit: 13 percent
Landform: Mountain slopes
Landform position (three-dimensional): Mountainflank
Down-slope shape: Concave
Across-slope shape: Linear

Gilpin, very stony

Percent of map unit: 5 percent
Landform: Mountain slopes
Landform position (three-dimensional): Upper third of mountainflank
Down-slope shape: Convex
Across-slope shape: Linear

Marrowbone, very stony

Percent of map unit: 2 percent
Landform: Mountain slopes
Landform position (three-dimensional): Upper third of mountainflank
Down-slope shape: Convex
Across-slope shape: Convex

FaF—Fedscreek-Shelocta-Handshoe complex, 30 to 80 percent slopes, very stony

Map Unit Setting

National map unit symbol: lh2h
Elevation: 800 to 2,000 feet
Mean annual precipitation: 28 to 47 inches
Mean annual air temperature: 42 to 67 degrees F
Frost-free period: 159 to 199 days

Farmland classification: Not prime farmland

Map Unit Composition

Fedscreek and similar soils: 30 percent *Shelocta and similar soils:* 30 percent *Handshoe and similar soils:* 25 percent *Minor components:* 15 percent

Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Shelocta

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank *Down-slope shape:* Concave
Across-slope shape: Linear
Parent material: Fine-loamy colluvium derived from sandstone and shale

Typical profile

H1 - 0 to 3 inches: silt loam
H2 - 3 to 27 inches: silt loam
H3 - 27 to 56 inches: very channery silt loam
Cr - 56 to 66 inches: weathered bedrock

Properties and qualities

Slope: 30 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 40 to 60 inches to paralithic bedrock
Natural drainage class: Well drained *Runoff class:* High
Capacity of the most limiting layer to transmit water (Ksat): Moderately high to high (0.57 to 1.98 in/hr)
Depth to water table: More than 80 inches *Frequency of flooding:* None
Frequency of ponding: None
Available water storage in profile: Moderate (about 7.6 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil Group:* B

Description of Fedscreek

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank *Down-slope shape:* Linear
Across-slope shape: Linear
Parent material: Coarse-loamy colluvium derived from sandstone and siltstone

Typical profile

H1 - 0 to 3 inches: sandy loam
H2 - 3 to 61 inches: sandy loam

R - 61 to 71 inches: unweathered bedrock

Properties and qualities

Slope: 30 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: 60 to 80 inches to lithic bedrock
Natural drainage class: Well drained *Runoff class:* Medium
Capacity of the most limiting layer to transmit water (Ksat): High (1.98 to 5.95 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None *Frequency of ponding:* None
Available water storage in profile: Moderate (about 8.5 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil Group:* A

Description of Handshoe

Setting

Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank *Down-slope shape:* Convex
Across-slope shape: Linear
Parent material: Loamy skeletal colluvium derived from sandstone

Typical profile

H1 - 0 to 7 inches: very channery loam
H2 - 7 to 66 inches: very channery sandy loam
H3 - 66 to 80 inches: very channery sandy loam

Properties and qualities

Slope: 30 to 80 percent
Percent of area covered with surface fragments: 1.0 percent
Depth to restrictive feature: More than 80 inches
Natural drainage class: Well drained *Runoff class:* Medium
Capacity of the most limiting layer to transmit water (Ksat): High (1.98 to 5.95 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None *Frequency of ponding:* None
Available water storage in profile: Moderate (about 6.1 inches)

Interpretive groups

Land capability classification (irrigated): None specified *Land capability classification (nonirrigated):* 7e *Hydrologic Soil Group:* A

Minor Components

Gilpin
Percent of map unit: 3 percent
Highsplint
Percent of map unit: 3 percent
Kimper
Percent of map unit: 3 percent
Marrowbone
Percent of map unit: 3 percent
Berks
Percent of map unit: 3 percent

uUduE—Udorthents-Urban land-Rock outcrop complex, 0 to 35 percent slopes

Map Unit Setting
National map unit symbol: 2mff5
Elevation: 700 to 2,100 feet
Mean annual precipitation: 28 to 54 inches
Mean annual air temperature: 42 to 68 degrees F
Frost-free period: 156 to 222 days
Farmland classification: Not prime farmland

Map Unit Composition
Udorthents, unstable fill, and similar soils: 50 percent
Urban land: 25 percent
Rock outcrop: 15 percent
Minor components:
10 percent
Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Udorthents, Unstable Fill

Setting
Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Mountainflank
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Loamy skeletal mine spoil or earthy fill derived from interbedded sedimentary rock

Typical profile
Ap - 0 to 5 inches: extremely parachannery silt loam *C1 - 5 to 30 inches:* extremely parachannery silt loam *C2 - 30 to 60 inches:* extremely parachannery silt loam *C3 - 60 to 79 inches:* extremely parachannery silt loam

Properties and qualities
Slope: 0 to 35 percent
Depth to restrictive feature: More than 80 inches

Natural drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately high (0.20 to 0.57 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None
Frequency of ponding: None
Available water storage in profile: Low (about 4.7 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 7s
Hydrologic Soil Group: C

Description of Urban Land

Setting

Landform: Mountain slopes

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8

Description of Rock Outcrop

Setting

Landform: Mountain slopes
Landform position (three-dimensional): Free face
Down-slope shape: Linear
Across-slope shape: Linear

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 8

Minor Components

Shelocta

Percent of map unit: 5 percent
Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Lower third of mountainflank
Down-slope shape: Concave
Across-slope shape: Linear

Cutshin

Percent of map unit: 3 percent
Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Lower third of mountainflank
Down-slope shape: Concave
Across-slope shape: Concave

Gilpin

Percent of map unit: 2 percent
Landform: Mountain slopes
Landform position (two-dimensional): Backslope
Landform position (three-dimensional): Lower third of mountainflank

Appendix V:

Rock Fork Creek and Howard Branch geochemical stream data at Truman Shepherd.

Location	Stream Depth (cm)	Electric Conductivity	pH	Temperature (C)
0 - Background	21.6	760	8	14.4
1 - Rock Fork	20.5	775	8	15.5
2 - Howard Branch	-	285	8	15.5
3 - Rock Fork	23	700	7.5	15.5

VITA

EDUCATION:

- **(2012-expected 2015) Doctor of Philosophy -** Dept. of Earth and Environmental Sciences, University of Kentucky. Dissertation - *The Environmental Effects of Coal Fires in Eastern Kentucky*.
- **(2008-2009) Certified Public Manager Program** - Dept. of Public Administration, Kentucky State University. Thesis - *A Comparative Analysis of Management Styles using McGregor's X and Y Theories.*
- **(2007-2008) Public Administration graduate-level coursework** - Dept. of Public Administration, Kentucky State University. Completed 12 hours towards master's degree in Public Administration.
- **(2002-2005) Master's degree** - Dept. of Geosciences, Eastern Kentucky University.
  Thesis - *Ground Water Velocity and Monitoring Well Reliability in Karst Environments.*
- **(1998-2002) Bachelor's degree** - Dept. of Geosciences, Eastern Kentucky University.
  Accolades - Sigma Gamma Epsilon Honorary Science Society, Officer of Geology Club.

ACADEMIC POSITIONS:

- **(2015-2016) Visiting Faculty (1-year assignment)**, Department of Geosciences, Eastern Kentucky University. Teach GEO 210 (Physical Geography), GLY 108 (Plate Tectonics), GLY 315 (Hydrology) and GLY 498 (Independent Study in Geosciences).
- **(2009-2014) Adjunct Geology Instructor:**
  - Department of Geosciences, Eastern Kentucky University (EKU). Taught: GLY 108 (Plate Tectonics) and GLY 315 (Hydrology).
  - Environmental Sciences, Bluegrass Community and Technical College (BCTC). Taught: GLY 101/111 (Introductory Geology/Introductory Geology Laboratory), GLY 110 (Environmental Geology), and GLY 220 (Introduction to Physical Geology).
- **(2002-2004, 2013-2015) Teaching Assistant:**
  - Earth and Environmental Sciences, University of Kentucky. Taught: EES 220 (Geology for Engineers), EES 130 (Dinosaurs and Disasters), EES 160 (Geology for Teachers).
  - Geology and Geography, Eastern Kentucky University (EKU). Taught: GLY 108 (Introduction to Physical Geology) laboratory, GLY 220 (Physical Geography), and NAT 171 (Concepts of the Physical World).
- **(2003) Upward Bound Earth Science Coordinator,** Berea College.

PROFESSIONAL POSITIONS (Other non-geology jobs available upon request):

- **(2012-2015) Visiting Research Scientist (part-time),** Center for Applied Energy Research (CAER) at the University of Kentucky. Research includes: petrography, rank, and preparation of coal and oil shale samples; researching coal-mine fire emissions; and coal sample collection from Kentucky power plants for geochemical analysis.
- **(2005-2011) Geologist III,** Energy and Environment Cabinet, Kentucky State Government. Project manager for ~50 facilities with soil and water contamination from leaking underground storage tanks. Worked specifically with BTEX, Lead, and PAH contamination.

PROFESSIONAL COMMUNITY SERVICE

(2012-2014) Vice President/President/Past President, American Institute of Professional Geologists – KY Section (AIPG-KY).
(2013-present) Executive Board Member, Kentuckians for Science Education.
(2011-2013) Faculty Coordinator of the Energy Club, Bluegrass Community and Technical College.
(2014-present) Executive Board Member, Geological Society of America - Student Representative.
(2013) Executive Board Member, American Institute of Professional Geologists (National).
(Currently) Member - American Association of Petroleum Geologists (AAPG), Kentucky Paleontological Society (KPS), Geological Society of Kentucky (GSK), Kentucky Academy of Science (KAS), Geological Society of America (GSA).

GRANTS/CONTRACTS/AWARDS/HONORS

(2014) Ferm Field Research Fund, University of Kentucky. Award.
(2014) Brown-McFarlan Field Research Grant, University of Kentucky. Grant.
(2014) Pirtle Fellowship, University of Kentucky. Fellowship.
(2014) 2nd Place, Graduate Student Oral Presentation Award, Kentucky Academy of Science. Award.
(2013) Massachusetts Institute of Technology (MIT) Energy Club National Meeting. Creative Activity/Grant.
(2013) GSA Coal Division's Antoinette Lierman Medlin. Award.
(2013) Spackman Research Grant, Society for Organic Petrology. Grant.
(2013) Bernadine Meyer Memorial Scholarship, Kentucky Society of Natural History. Scholarship.
(2012) Teaching Environmental Geology, NSF Grant, Bozeman, MT. Creative Activity.
(2011) Bluegrass Community and Technical College Innovation Award. Teaching.

PUBLISHED WORKS

Garrison, T., Hower, J.C., Fryar, A., In review. Hydrocarbon contamination (with focus on BTEX and PAH) in soil and ground water at two eastern-Kentucky coal fires.

Garrison, T., Hower, J.C., Henke, K.R., O'Keefe, J.M.K., Stracher, G.B., 2014. A review of sampling methods in coal fire studies. In G.B. Stracher et al., *Coal and peat fires: A global perspective*, vol. 1, Elsevier, chapter 29.

Garrison, T., 2008. Energy and Environment: *Why is Understanding Geology Important*? Public outreach document, Kentucky Section of the American Institute of Professional Geologists, Outreach Committee. 6p.

Garrison, T., 2005. A Study of Monitoring Well Reliability and the Aggressive Pumping Method in a Karst Terrane Sinking Valley, Pulaski County, Kentucky. Master's Thesis, Eastern Kentucky University, Richmond, Kentucky. 88 p.

Dai, S., Yang, J., Ward, C., Hower, J.C., Liu, H., **Garrison, T**., French, D., O'Keefe, J.M.K., 2015. Geochemical and mineralogical evidence for a coal-hosted uranium deposit in the Yili Basin, Xinjiang, northwestern China. Ore Geology Reviews, 70, 1-30.

Belkin, H.E., Hower, J.C., O'Keefe, J., **Garrison, T**., Johnston, M., 2013. Cenozoic coals of Southeast Asia (Malaysia, Philippines, and Thailand): Petrology and Geochemistry. The Society for Organic Petrology, Sept 2-4, Sosnowiec, 2013.

Hower, J.C., Hoffman, G.K., **Garrison, T.**, 2013. Macrinite and funginite forms in Cretaceous Menefee Formation anthracite, Cerrillos coalfield, New Mexico. International Journal of Coal Geology, 114:54–59.

Hower, J.C., O'Keefe, J.M.K., Henke, K.R., Wagner, N.J., Copley, G., Blake, D.R., **Garrison, T.M.,** Oliveira, M.L.S., Kautzmann, R.M., Silva, L.F.O., 2013. Gaseous emissions from the Truman Shepherd coal fire, Floyd County, Kentucky: A re-investigation following attempted mitigation of the fire: International Journal of Coal Geology, 116-117:63-74.

Hower, J.C., Mitz-Keenan, M., O'Keefe, J.M.K., Mastalerz, M., Eble, C.F., **Garrison, T.**, Johnston, M.N., Stucker, J.D., 2013. Macrinite forms in Pennsylvanian coals. International Journal of Coal Geology, 116–117:172–181.